Testing macroscopic traffic evacuation models for wildland-urban interface fires

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Abstract
This thesis presents the verification and validation testing performed on the evacuation simulation platform WUI-NITY which has the aim of being a simulation tool for the integration of different layers, such as pedestrian, traffic and wildfire with evolving dynamic interactions. The present thesis aims at applying a set of verification tests and validation testing suitable for WUI-NITY with a focus on the traffic component. This is deemed to evaluate the calculation model, assumptions and set ups in WUI-NITY. This is performed through the analysis of results produced by the software and to make, if necessary, changes and modifications to the tests to better evaluate WUI-NITY predictive capabilities. The validation is performed on a single core traffic component, the relationships between speed-density and flow-density on highways, a commonly used road type in evacuations. This is performed by comparing theoretical underlying assumptions with the case study of the Kincade Fire 2019 where evacuation traffic used, among other roads, the Highway 101. The traffic data is sourced from the California Department of Transportation and is used to create speed-density and flow density relationships through the application of regression models, for both routine and evacuation traffic. An iterative loop procedure is applied on verification testing. This resulted in the tests producing results with negligible differences between simulation and hand calculations. The validation performed showed that the theoretical relationships adopted in WUI-NITY (based on the Lighthill-Whitham-Richards model) present some differences in the highest density region. The theoretical peak flow is higher than what the validation data suggest, while the routine traffic has a higher flow and speed than the evacuation traffic. While the theoretical speed-density and flow-density relationships reach a value of 0 after a certain density threshold is reached, the measured data suggests that there is an average minimum speed and flow that can be considered averaging data over 5 min. Further validation testing is necessary to get a complete picture on how the speed and flow in routine and evacuation traffic changes with increasing density, with additions to other road types and validating the other modelling components included in WUI-NITY.
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Summary

Previous works on developing a wildland-urban interface (WUI) fire evacuation platform that integrates pedestrian, traffic and fire into a single model has had a mixed success. Most of the traffic simulation models integrate wildfire by having the fire dynamically affecting communities and their need to start their evacuation, at which the fire becomes static and non-changing while the traffic evacuation continues through fixed and set conditions. This is not a realistic representation of the wildfire impact since it is dynamically changing with environmental conditions and weather phenomenon, producing simulation results that do not accurately represent the traffic evacuation through an evolving wildfire scenario in the wildland-urban interface. In addition, models generally put greater emphasis on one of the modelling layers affecting WUI fire safety, rather than adopting a consistent level of granularity.

These issues led to the development of the WUI-NITY platform, which aims to integrate the pedestrian, traffic, and fire layers into one tool with developing conditions and integration between the layers. Being the platform first of its kind, there is a lack of standardized verifications tests developed to check the accuracy of predictions in the calculation models adopted for representing the different components and functions in use. In addition, there are extensive validation testing cases to check the calculation models against, i.e., their ability to re-produce realistic results compared to real life scenarios.

There is currently no official documentation on what verification testing that needs to be performed in this type of simulation model. In contrast, standard protocols exist for the verification and validation of pedestrian evacuation in building fires (e.g. ISO 20414) where indications concerning components testing could be found, such as movement speed in congestions and smoke, route and exit choices, relationships between speed, flow, and densities, etc. The present work builds upon the work done in the building context and runs a set of traffic-related tests developed in collaboration with the WUI-NITY team.

The verification tests were designed and developed with macroscopic models in mind, given the possibly large temporal and spatial scale of the problem. In the present work, the thesis had a focus on traffic modelling testing. The completed tests were applied in WUI-NITY with help of the development team, where the results were used to improve upon the calculation models, assumptions and software set ups, until WUI-NITY produces results with negligible discrepancies. The tests were hard-coded in the source of the tool in order to allow running them automatically at each software update. The tests developed describe objective, geometry, scenario, expected results, test method and user’s actions for each test. The reported results were put in a standardized reporting template based on ISO 20414.

Validation testing cannot, unlike the verification testing, reach an end where no more testing is needed. The validation testing can make the tested component good enough in terms of accuracy and representability, but more validation can always be done to improve the quality of the calculation model. There is a large range of components to be tested in a software considering pedestrian response, traffic movement and wildfire spread, so a simple preliminary validation was made to one of the fundamental components in the traffic layer, the relationship between speed-density and flow-density. The validation was performed by comparing the speed-density and flow-density relationships for a road type commonly used, between the

theoretical relationship used for highways in WUI-NITY and actual measured traffic data for a real evacuation case where highways among other road types were used in the evacuation.

To perform the validation test, a place where data could be sourced with high level of detail and access had to be identified. The data used were sourced from the California Department of Transportation (Caltrans) through their database Caltrans Performance Measurement System (PeMS). The data searched for contain measurements on speed, flow and densities that were reported in the traffic during the Kincade Fire 2019, a well-documented case with much information on evacuation and has been subjected to other research reports as well. Data were extracted for evacuation traffic from after the fire ignition, as well as routine traffic observed before the fire ignition. The data were treated and used to construct speed-density and flow-density relationships through regression models based on the measured data. The constructed relationships were then compared with the theoretical WUI-NITY speed-density and flow-density relationships.

The validation testing showed that the maximum flow observed at routine and evacuation traffic is lower than what the theoretical relationship assumes. Routine flow and speeds are overall higher than evacuation flow for all observed density levels. There is an observed limitation of density ranges for the theoretical relationship, i.e., the flow and speed get reduced to 0 at a much higher rate than for the routine and evacuation data. This difference is likely due to the actual data approximation (every 5 min). While the speed-density and flow-density reaches a value of 0 after a certain density due to underlying assumptions, the measured data suggests that there is a minimum speed and flow no matter how high the density is increased. This suggestion could be implemented in WUI-NITY assumptions to produce more realistic results, but further validation is needed to investigate under which conditions this could be a credible assumption.

Sammanfattning

Tidigare genomförda arbeten i att utveckla en wildland-urban interface (WUI) plattform för evakuering av brand som integrerar fotgängare, trafik och brand till en gemensam model har haft blandade framgångar. De flesta modeller för trafiksimuleringar integrerar brand genom att låta branden på ett dynamiskt sätt påverka ett samhälle och deras behov att börja evakuera, för att därefter låta branden bli statisk och oförändrad medan trafikevakueringen fortsätter genom fasta och förbestämda föhållanden. Detta är inte en realistisk representation av en brands påverkan eftersom den ändrar sig dynamiskt med omgivningens förhållanden och väderlek, vilket producerar simuleringsresultat som inte noggrant representerar trafikevakuering genom en utvecklande brand i WUI. Dessutom lägger modeller generellt mer betoning på en av de modellerade nivåerna som påverkar brandsäkerhet i WUI, istället för att anta en jämn nivå av granularitet.

Dessa problem gav upphov till utvecklingen av plattformen WUI-NITY, som syftar till att integrera de olika nivåerna för fotgängare, trafik och brand till ett verktyg med utvecklande förhållande och integration mellan nivåerna. Eftersom denna plattform är den första av sitt slag, saknas det standardiserade verifikationstester utvecklade för att kontrollera noggranhet av förutsägelser i beräkningsmodeller antagna för representation av de olika komponenter och funktioner som används. Dessutom finns det omfattande valideringsfall att kontrollera beräkningsmodellerna emot, d.v.s. deras förmåga att återskapa relisitskt resultat jämfört med verkliga fall.

Det finns för nuvarande ingen officiel dokumentation för vad verifikationstester behöver testa i denna typ av simuleringsmodel. I jämförelse finns det standardprotokoll för verifiering och validering av personevakuering vid brand i byggnad (t.ex. ISO20414) där indikationer som berör komponenttester kan hittas, sådana som förflyttningshastighet i köer och rök, väg- och utgångsval, förhållanden mellan hastighet, flöden och densitet etc. Det presenterade arbetet bygger vidare på det arbete som genomförts i byggnadssammanhang och testar en uppsättning av trafikrelaterade tester utvecklade i sammarbete med WUI-NITY-teamet.

Verifikationstesterna var designade och skapade med makroskopiska modeler i åtanke, givet möjligheterna för stora skalor i tid och rum av problemet. I det nuvarande arbetet fokuserar avhandlingen på tester för trafikmodellering. De färdigställda testerna tillämpades i WUI-NITY med hjälp av utvecklingsteamet, där resultatet användes för att förbättra beräkningsmodeller, antaganden och programvaruinställnigar, till dess att WUI-NITY producerade resultat med försumbara avvikelser. Testerna var hårdkodad i källkoden av verktyget för att kunna tillåta dem att köras automatiskt vid varje mjukvaruuppdatering. De färdigställda testerna beskriver mål, geometri, scenario, förväntat resultat, testmetod, och användarens tillämpningar. Det rapporterade resultatet noterades i en standardiserad rapporteringsmall baserat på ISO 20414.

Valideringstesterns kan inte, till skillnad från verifikationstesterna, uppnå ett slut där ingen mera testning behövs. Valideringstesterna kan göra de testade komponenterna tillräckligt bra i form av noggranhet och representabilitet, men mer validering kan alltid genomföras för att förbättra kvaliteten av beräkningsmodellerna. Det finns en stor uppsättning av komponenter att testa i en mjukvara som tar hänsyn till respons av fotgängare, trafikrörelser och brandspridning, vilket gjorde att en simpel perliminär validering utfördes på en av de funamentala

komponenterna i trafiknivån, nämligen förhållandet mellan hastighet och densitet samt flöde och densitet. Valideringen genomfördes genom att jämföra teoretiska förhållanden användna för motorvägar i WUI-NITY med uppmätt trafikdata för ett verkligt evakueringsfall där bland annat motorvägar användes i evakueringen.

För att genomföra valideringstestet behövdes en källa där lättillgänglig data med hög detaljeringsgrad kunde samlas in. Den data som användes samlades från California Department of Transportation (Caltrans) genom deras databas Caltrans Performance Measurement System (PeMS). Datan som sökdes efter innehöll mätningar om hastigheter, flöden och densiteter som var rapporterade i trafiken under branden i Kincade 2019, ett väldokumenterat fall med mycket information kring evakueringen och har även varit ämnesområdet för många andra forskningsrapporter. Datan behandlades och användes för att skapa ett förhållande mellan hastighet och densitet samt flöde och densitet genom regressionsanalys baserat på den uppmätta datan. De konstruerade förhållanden jämfördes därefter med de teoretiska förhållanden mellan hastighet och densitet samt flöde och densitet som används i WUI-NITY.

Valideringstesterna visade att det maximala flödet observerat vid rutin- och evakueringstrafik är lägre jämfört med vad de teoretiska förhållanden antar. Flöde och hastigheter vid rutin är överlag högre jämfört med evakueringsflöden för alla observerade nivåer av densitet. Det finns en observerad begränsning av densitetsintervall för de teoretiska förhållanden, d.v.s., flödet och hastigheten reduceras till 0 i en mycket högre takt jämfört med rutin- och evakueringsdata. Denna skillnad beror troligtvis på att den faktiska datan är approximerad (var 5:e minut). Medan hastighet och densitet samt flöde och densitet når ett värde av 0 efter en specifik densitet på grund av underliggande antaganden, föreslår den uppmätta datan att det finns en minimum hastighet och flöde oavsett hur mycket densiteten ökar. Detta förslag kan implementeras i antaganden för WUI-NITY till att producera mer realistiska resultat, men utökad validering är nödvändigt för att undersöka under vilka omständigheter detta kan vara ett trovärdigt antagande.

Nomenclature

d	Density (vehicles/km/lane)
Q	Flow (vehicles/lane/hour)
v	Speed (km/h)

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1. Introduction

Wildfires are a serious threat in many regions around the globe, affecting both urban and rural areas alike. The fires affect personal health and infrastructure in both short- and long-term aspects damaging both ecological systems and the overall economy with billions of US$ in losses (Hardy, 2005) (Thomas, et al., 2017).

The severity of wildfires is directly influenced by the historical changing climate conditions. The change brings forth stronger winds with hotter and drier summers, increasing the number of burnable areas and frequency of long fire weather seasons (Jolly, et al., 2015).

Wildland-Urban Interface (WUI) Communities are defined as “the urban wildland interface community exists where humans and their development meet or intermix with wildland fuel.” This definition describes three different categories of communities; interface, intermix, and occluded. The Federal agencies’ focus is on the first two sub-communities, which in turn are defined differently. (USDA, USDI, 2001) The Wildland-Urban Interface is defined as “geographical area where structures and other human development meets or intermingles with wildland or vegetative fuels“, while the Wildland-Urban Intermix is defined as “an area where improved property and wildland fuels meet with no clearly defined boundary“ (Intini, et al., 2017).

WUI communities have grown rapidly during the latest decades and have the greatest risk of being affected by wildfires due to the proximity to flammable vegetation (Radeloff, et al., 2018). Most of the ignitions of wildfires occur in the WUI, where they frequently burn houses and are difficult to fight (Radeloff, et al., 2018).

The thousands of WUI communities that continues to grow may hold a road network which may not enable rapid evacuation since more households are linked up to the road network. Planners and residents are focusing more on structure protection, while the egress issues go by unnoticed, which are a result of narrowed roads, irregular intersections, and few exits. (Cova, 2005).

During the Camp Fire 2018 the evacuation were both chaotic and rapid. The hastened evacuation caused congestion, forcing some evacuees to abandon their vehicles and leave on foot, and giving officials difficulties on reaching their needed location to assist with the evacuation (Wong, et al., 2020). In the Atlas Fire 2017 the only road used for entering and exiting the community of Atlas Peak was blocked by downed trees making traditional escape via car impossible. The people trapped had to be helicoptered to safety in the absence of available traffic evacuation routes (Ronchi, et al., 2021).

To help the WUI communities, WUI fire evacuation models are developed with two main scopes. First, enhance situational awareness to consider what-if scenarios during evacuation planning and second, provide decision support for real time emergency management (Intini, et al., 2019). There is however a limited number of traffic evacuation models and studies that addresses WUI fires compared to other hazards, such as hurricanes. (Intini, et al., 2019).

Among current research efforts, an international research team is working on developing a new modelling platform called WUI-NITY that considers three different layers: fire, pedestrian, and traffic (Wahlqvist, et al., 2021). The interaction of all the layers and the ability to exchange information with each other makes it a simulation with dynamic information output. It can produce vulnerability maps pointing out weaknesses in WUI communities' traffic evacuation networks (Wahlqvist, et al., 2021). The platform is a continuation of previous research to produce specifications needed for such simulation framework and to highlight research issues (Ronchi, et al., 2019)

The use of simulation models as a tool must be associated with reliability of results and accuracy. The calculation methods in use need to be verified for mathematical accuracy and validated for capability to reproduce the phenomena. The verification and validation (V&V) of calculation methods provide an assurance for its users and to those who are asked to accept the result. In other words, they ensure that the calculation methods provide a sufficiently accurate prediction of the course and consequence of a fire in a specific planned application (ISO/TC 92/SC 4, 2015).

To ensure V&V, a set of verification tests need to be developed as well as providing reliable data-sets to be useful for validation. For pedestrian evacuation, especially in buildings, there has been research done to produce a standardization for V&V in building evacuation models (Ronchi, et al., 2013). In contrast to the pedestrian evacuation, there are few studies about V&V for large scale traffic evacuation models, that takes into consideration fire progression, pedestrian movements, and traffic flows (Ronchi, 2020).

In the development of a simulation platform like WUI-NITY that considers interaction between three different layers, there is a need for V&V to ensure the calculation methods are making accurate enough predictions and that the interactions work as intended. There is however no available set of verification tests designed for traffic evacuation from WUI, considering its interaction with fire and pedestrian. The model also needs to be validated with data from a real case to ensure the model can provide accurate enough representation of the real world.

To be able to verify and validate a WUI evacuation model that considers fire, pedestrians, and traffic, a set of verification tests needs to be designed, and their applicability should be checked. The WUI-NITY platform uses a macroscopic modelling approach, which is important to have in mind when developing the verification tests since macroscopic models are the main focus. An exemplary application of the tests is done by running the tests in WUI-NITY and the results are compared with hand-calculated expected results. In addition, a simple validation is performed using traffic-related data collected during the Kincade Fire 2019. Theoretical relationships concerning speed-density and flow-density are compared with extracted real world data for speed-density and flow-density in both routine non-emergency traffic and evacuation traffic. The speed-density and flow-density relationships is sometimes called fundamental diagram, a terminology that has been sometimes criticized in the literature (since there are many "fundamental diagrams") but is used here to refer to the speed-density and flow-density relationships.

1.1. Purpose and objective

The purpose of this thesis is to increase the accuracy of the simulation model WUI-NITY investigating its traffic evacuation modelling component and its interaction with fire and pedestrian modelling.

The objective of this thesis is to design verification tests for the traffic component of WUI evacuation models and produce a simple validation test for a key core traffic component in WUI-NITY (i.e. speed-density and flow-density relationships):

- Defining and designing the verification tests for macroscopic traffic models used for WUI fire applications.
- Testing their use through application with WUI-NITY.
- Doing a simple preliminary validation by testing a core traffic component through comparison with traffic evacuation data from Kincade fire 2019.

1.2. Limitations and delimitations

In fire safety engineering exists the sub-field of evacuation modelling which include verification and validation of the models used to predict the outcome of a simulation. For this thesis work, in the terms of verification and validation, the focus mostly lies on the verification of evacuation models. Given the planned real-time application of those tools, WUI fire evacuation models are in turn mostly focused on macroscopic modelling. The sheer size of the geographical areas and number of vehicles that could be simulated in the evacuation model for WUI generally makes macroscopic models better suited for the task. This limits individual driving behaviors to be simulated. The list of factors to be tested in the verification process for WUI evacuation models makes the objective extensive. The factors to be tested primarily revolves around the traffic component, with few interactions between traffic and pedestrian, and traffic and fire. As the work of producing a verification test list to be tested in a simulation model proceeds, the number of relevant factors to test keeps growing. While there may be many more tests to be run, it was decided to keep it to a reasonable and manageable size at this first stage of research in this domain. The factor test lists can be extended in future works.

Validation requires experimental data-sets on human behavior or detail information gathered from real fire evacuations which is scarce and makes it difficult to validate evacuation modelling tools. Since the focus of the thesis lies primarily on verification tests, only a preliminary simple validation test has been designed to facilitate the definition of future validation efforts. This performed considering that a wider range of possible behaviors and scenarios representing the evacuation process needs to be included in the data-sets used as benchmark for validation. While a validation test can be made from one fire evacuation case, the validation can always be improved upon by validating with more documented cases and scenarios.

2. Background

This section presents background information relevant to the thesis work covering information about WUI fires, assumptions and findings concerning pedestrian and traffic modelling, what WUI-NITY is and the use of modelling tools in risk management.

2.1. WUI fires

The wildland-urban interface (WUI) is a zone where human settlements are adjacent to or intermixed with wildland vegetation. The term is mostly used in the context of highlight areas at risk from wildland fires. When wildland fires reach the WUI, they can then instead be called WUI fires (Johnston, et al., 2020) (USDA, USDI, 2001).

In Europe the abandonment of rural areas and depopulation of villages have changed the land use and forest exploitation, increasing the risk of wildfire as the vegetation expands. A variety of factors can change the impact of WUI fires including vegetation, weather, topography, type of urban development, human population, ignitions, fire management, and the socioeconomic and political contexts (Johnston, et al., 2020)

The risk from WUI fires have during the recent decades increased due to the expansion of the WUI in the USA, with an increase of houses in the WUI with a growth of 41 % since 1990 and the overall WUI covered 9,5 % of the conterminous United States in 2010 (Radeloff, et al., 2018). It is a trend that can be observed across the globe where more people are moving to places surrounded by nature and vegetation. Thera are many factors the increasing expansion of WUI, such as population growth, recreational activities, retirement to rural areas and economic reasons (Johnston, et al., 2020).

The dangerous WUI fires causes heavy losses of life and property, with heavy socioeconomic effects. The WUI fires are a global issue with many countries having faced difficult situations in the past, e.g., Australia 2019, Canada 2016, Portugal 2017, Greece 2018, California 2017-2018. Each time these large scale WUI fires are raging, around 100 people loses their life, thousands of homes and buildings are destroyed and billions of US$ in insurable losses, with probability of more economic losses indirectly through industrial shutdowns and large-scale evacuations (Johnston, et al., 2020).

According to climate change research, the WUI communities will in the future have to deal with an increase in fire frequency and intensity (Jolly, et al., 2015). The wildfire management and mitigation systems will be able to suppress some of the predicted impacts. It is likely however that the increased fire activity together with the heightened demand on fire suppression will in the future result in great costs to communities for their wildfire management and suppression as well as devastating losses in WUI fires. (Johnston, et al., 2020)

2.2. Evacuation Modelling in WUI fires

Along with wildfire spread, two main components should be considered when modelling WUI evacuation, namely pedestrian and traffic evacuation. Existing modelling approaches for those components are here briefly discussed.

In egress building models there is a need to include the representations of behavioural aspects of evacuee performance. For wildfire evacuation models there seem to be an equal need to include behavioural aspects for them to be useful, although not all do that. Complexities of modelling evacuee behaviour during a serious wildfire threat may be greater than for those evacuating buildings due to multiple factors potentially affecting residents' responses to wildfire threat. For these models to be useful they need to include detailed location-specific information about the residents' probable response after an evacuation warning has been issued. To get this information officials with responsibility for wildfire safety need to collect and monitor psychosocial information about 1) residents' level of perceived wildfire risk, wildfire safety plans, and wildfire safety preparations, in relation to 2) their key demographic characteristics such as age, household composition, special needs, transport options and pet and livestock ownership, and 3) the warning and threat history of the location. (McLennan, et al., 2019)

Attempts have been made to use a mathematical framework to predict householders' perceived risk with wildfires and how they take protective actions in response to threat. A presented conceptual Wildfire Decision Model based on nine assumptions derived from existing literature on human behaviour in wildfires and models developed for other large-scale emergencies, such as hurricanes. The proposed modelling framework allows for four different states of the householder behaviour (normal, investigating, vigilant and response) to be identified as well as the protective action response of the householders (i.e., leave, shelter in place, or defend). In the literature there are different modelling solution to human decision-makings during disasters such as, Fuzzy Theory, Neural Network, rule-based models, etc. The model should have a probabilistic structure that can simulate human behavioural uncertainty, which leads the framework to belong to the random utility models. The proposed framework could then when imbedded in a simulation platform provide a tool that generates new dynamic travel demand models for large-scale evacuation due to fires. (Lovreglio, et al., 2019)

An important aspect to consider in the pedestrian models is the protective action decision-making and behaviour of people in the WUI, i.e., what they do in response to a wildfire. Choosing to evacuate or to take a protective action is complex process influenced by multiple diverse factors that include sociodemographic factors, social and environmental cues, preparation and experience, familial responsibilities, location, and credible threat and risk assessment. Although these factors are difficult to insert in models used, they are important to include in WUI fire evacuation models as they influence when or if they decide to evacuate and where they will go. (Folk, et al., 2019)

The residents around WUI show various responses to the bushfires. While fire and rescue services tend to see householders as either evacuators or remainers, there are more ways to react to wildfire than just these two. The essentially binary approach of the bushfire-safety policy 'Prepare, stay and defend or leave early' does not properly display the reality of what people go through in a wildfire emergency. (Strahan, et al., 2018)

In most wildfire evacuation events involving an evacuation warning from officials there are residents who will not comply with the order, some who wait until their safety is being compromised and those who will attempt to return to their property if they are away when the warning is issued (Rigos, et al., 2019). Those who do not evacuate while a warning is in place are mostly motivated by the need to protect their valued assets (including pets and livestock) which could otherwise be believed to perish if not attended. Most people who delay their evacuation do not have a pre-event plan to evacuate. Others have failed in engaging in the idea that the wildfire can threaten their property and life in a future event. Some consider the wildfire as a threat, but that probability is too low for protective action. Some have accepted that wildfire can pose a threat and have planned to evacuate but wait and see if it is really necessary unless their life is evidently in danger. For some residents, the evacuation will be delayed due to difficulties surrounding life circumstances, such as age disability, social isolation, or other disadvantages. (McLennan, et al., 2019)

Whether the residents will refuse to comply with the evacuation order or delay their evacuation might be caused by contextual factors. These might include a policy if the evacuation is mandatory or optional, and if it is mandatory, enforcement practices; authorities' wildfire risk rating of the affected area and previous wildfire history; the effectiveness of authorities' prior promotion of wildfire safety and education; the property mix of amenity residences and farming and agribusinesses; the egress road network, and the demographic makeup of the residents. (McLennan, et al., 2019)

For example, in the 2017 October Northern California Wildfires 100,000 people were forced to evacuate from the Sonoma, Napa, and Solano Counties, together with multiple reginal medical facilities. During the evacuation, the residents had issues with power outages preventing them from opening their garages, downed trees blocking vehicles, congestion on evacuation routes, and road closure. The speed at which the fire approached forced some people to abandon their vehicle and evacuate on foot. During the wildfire, the Atlas fire blocked off the only road leading to and from the community in Atlas Peak. The residents had to be evacuated using emergency helicopters to reach safety. Even local and regional transit services were used to evacuate people from assisted living facilities, apartments, homes, and hospitals in and around the areas of Napa. (Wong, et al., 2020)

In the 2018 November Camp Fire, the Butte County in California and the town of Paradise were severely impacted. The Camp Fire led to a disaster of an evacuation and was one of the deadliest wildfires in the United States history. Despite the officials plans to do a phased evacuation, mishaps in the communication and the rapid approach of the fire forced all the Paradise residents to evacuate all at the same time causing considerable congestion on the evacuation routes. With the continual growth of the fire and the increasing congestion, people had to drive in the road shoulder to keep distance from the flames and in some cases had to escape on foot. (Wong, et al., 2020)

Regarding the representation of traffic, modelling tools have shown great potential for both evacuation planning and real-time emergency evacuation. Most modelling cases address hurricane traffic evacuation and only a small portion focuses on WUI fires (Intini, et al., 2019). Most of them uses the wildfire to calculate when to order an evacuation, with the wildfire being a static event that no longer affects the traffic evacuation. A better way to handle the traffic simulation would be to integrate the wildfire layer with the traffic layer to have dynamic conditions that changes the outcome of the traffic evacuation over time. This could be helpful for large communities with few exit points in supporting the planning for the evacuation and real-time decision support for rescue services. The larger communities have a need for higher capacity roads, since their traffic density will peak for short moments in an evacuation. Limitations in available road networks for these large communities can be problematic when their large traffic volumes. (Intini, et al., 2019).

When deciding what travel modelling to use, the decision is either trip-base or activity-based. Both are similar that the start at an origin and reaches a destination. For the tip based modelling, this means just going from start to finish. For the Activity based modelling this can evolve into multiple destinations to perform the activity, e.g., picking-up family members away from the house. There are also those that do not consider evacuating at all, which need to be included in the trip generation. Those that do evacuate have to reach a destination of some sort, which can be an emergency shelter, homes of friends and relatives, hotels etc. in the case where the evacuation started from their household, but in some cases their own house can be a safe place depending on the situation and where they started evacuating from (Intini, et al., 2019).

The choice of transportation for evacuation in WUI fire evacuation tends to be vehicles traveling on roads, such as cars, buses, trucks, caravans etc. In some cases, there are also a need for other types of evacuation transport if all road networks have been closed off by the fire. In those cases, transportation by air or sea is a viable option to include in the modes of transportation. Background traffic is another important factor to include in the traffic evacuation modelling, which can include the presence of normal traffic that does not drive on the road with the intention of evacuation at the moment, shadow evacuation where people evacuate before an evacuation order is given and rescue services called in. Taking these into account is useful so that the traffic system gets overwhelmed by underestimating the amount on traffic in place. The scale of which the modelling uses is important to consider for the scale of which the WUI fire evacuations will simulate. Computer simulation power, time and resources can affect if a macroscopic, microscopic or a hybrid mesoscopic simulation approach should be used. The chosen approach also dictated what can of verification test can be performed in the simulation. (Intini, et al., 2019)

2.3. The WUI-NITY platform

WUI-NITY is a modelling platform that couples modelling layers considered to affect the evacuation performance (e.g. fire, pedestrian and traffic) into a single modelling environment. The WUI-NITY program is created with the UNITY 3D game engine. The use of UNITY 3D allows for an easy coupling by using it as a host for the sub-models, given its modularity. The granularity of a model can be changed from a macroscopic model to a microscopic model if the detail of the result and computational power available were to change. The data being transmitted between the sub-models as input and output data are using the same type of format that allows them to exchange new data with each other as the simulation proceeds. (Wahlqvist, et al., 2021)

While there are many other simulation models available that can assess the impact of WUI fires and inform of where necessary mitigation is needed, they all have their limitations, primarily in their inability to showcase evolving scenarios in the event of fire, from fire spread, decision making and traffic movement. The existing models can represent their own layer in isolation, with difference in granularity, of fire, pedestrian, or traffic performance level. This created the need for a public available and affordable platform that can predict evacuation performance including the impact of different responses, resources, and incident scenarios. Simulation models are a powerful tool for officials and planners to be informed of weaknesses in fire mitigation systems of the WUI communities. They can be used to estimate how an evacuation develops based on current of future fire scenarios, the given population, their accessibility to different resources and decision making (Intini, et al., 2019).

The purpose of the WUI-NITY platform is to increase situation awareness of first responders and residents during the evacuation scenarios by providing with new information derived from the continually dynamic evolution of the emergency. The output produced by the WUI-NITY platform are mainly predictions generated by the coupled models, which is a distinctive feature. These features enable the system to map put the dynamic vulnerability which represents the capacity or lack of capacity in the simulated populations to cope with the present conditions given the available resources. The information regarding dynamic vulnerability provided by the WUI-NITY platform is beneficial for evacuation planners and emergency responders, as it offers an opportunity to evaluate the dynamic vulnerability of an area given fire scenarios and evolving conditions. The user of WUI-NITY can be someone working at the emergency services or by officials in the county. While much of the input data in the simulation are provided from different databases, the user can investigate different what-if fire scenarios and see how the evacuation process changes in different circumstances. WUI-NITY has the potential to support WUI communities through its implementation by allowing better planned training and practices throughout and in preparation for WUI fires (Ronchi, et al., 2019).

2.4. Risk management of WUI fires

Risk assessment is a major part in the risk management process and should be done systematically and iteratively. Risk assessment is generally done through three steps; 1) Risk identification, 2) risk analyze and 3) risk evaluation. The risk identification is about finding, recognizing, and describing risks that could potentially prevent an organization from achieving its objectives. Depending on the scope for the risk management, the identification of risks should be done to the appropriate level in comparison to the system the risk management is applied upon. The risk analysis considers the nature of risk and their characteristics such as level of risk. They involve detailed consideration of uncertainties, risk sources, consequences, likelihood, events, scenarios controls and their effectiveness. Risk analysis can be done as qualitative or quantitative, depending on the desired level of risk assessment, how much time and resources are available and if there are any legal requirements surrounding the conduction of risk management. In the risk evaluation the decision if risk reduction is necessary or treatment based on the result of the risk analysis in comparison to the risk criteria. (ISO/TC 262, 2018)

From the perspective of risk management for WUI fires, the usage of verified tools for mapping vulnerability can primarily be used in the risk assessment. To see the vulnerability in the capacity of the evacuation system is what the risk identification is used for. These verified tools that could map the vulnerability are also those that can become part in the analysis of the vulnerability. Through the identification analysis of the vulnerabilities and risks generated by the verified tools, you can accurately make a risk evaluation if there is a need to take the risks into consideration for a risk treatment.

The use of simulation tools is present in multiple steps in the risk management process. They are not just present in their own steps, the early stages of the risk management process performed with tools affect the later steps. If the tools used have been verified, the right risks can be identified, analyzed in the right way, be evaluated with the right basis, and risk assessment will be completed successful. If the tool on the other hand is not verified, it can then identify risks where there are none, analyze risks the wrong way, be evaluated in the wrong way, and make a wrong risk assessment. Best case scenario is that the risk assessment analyzes the right risks and make the right evaluation of them and implementing correct risk reduction, improving the system through the use of verified tools. Worst case scenario is that the risk assessment is performed with non-verified tools and analyzes risks that do not exist and make an evaluation that leads to risk reduction where it is not needed and ignore or worsen risk reduction system where it is needed the most.

When that is applied to WUI fires, the verified or non-verified tools can be a decisive factor if an evacuation from a WUI community is proceeding as intended. If verified tools are used in the right place, official planners and fire department can both work on a proper risk management early in the building phase as well as during an emergency evacuation. The tools can then ensure that emergency responders and residents improve their planning and training in risk management.

Wildfires can cause devastating damage on WUI communities, most significantly loss of life. The safety of these at-risk populations is depending on the accuracy of risk assessment and emergency planning. Evacuation modelling and simulation systems are necessary tools for implementation of such planning and decision making. People's behavior during wildfire evacuation is a key factor for the outcome. What people do and when they do it are largely depending on the spatio-temporal distribution of events in a scenario. (Beloglazov, et al., 2016)

Wildfires are an important safety risk to address for populations living in the WUI. A way to assess the impact of wildfires in the WUI communities and provide officials and planners with information on ways to mitigate negative consequences is via simulation models. These simulation tools are being increasingly used throughout the WUI communities to inform of the development of evacuation plans. (Wahlqvist, et al., 2021)

An example of a WUI fire where the implementation of the WUI-NITY tool could have been of useful assistance was the wildfire in Västmanland, Sweden 2014 where the wildfire enveloped 13000 hectare and about 1000 people and 1700 livestock had to evacuate (Skogsstyrelsen, 2021). A widespread fire leading to evacuation could be simulated in WUI-NITY to provide the emergency services with accurate predictions on how fast the fire could spread if the road network has enough capacity for the evacuation and how much time the evacuees would have to put themselves in safety. While WUI fires and traffic evacuations in Sweden are relatively small in Sweden compared to international wildfires (SkogsSverige, 2021), the use of the simulation tool WUI-NITY can still be applied to the evacuation decision making by the emergency services.

3. Methodology

In the beginning of the work, a literature research was conducted to the underlying causes of WUI fires, the general idea of what needs to be included in evacuation modelling in WUI fires, what the WUI-NITY platform is and the basics on how it works, as well as how risk management can be handled in WUI fires using verified tools. This in the context of traffic evacuation modelling for WUI fires provided an insight on what to include in the initial V&V of the WUI-NITY model. At this point the best method to handle the objectives of the thesis had to be considered. WUI-NITY being a newly developed model and the author of this thesis having only basic knowledge on coding and simulation modelling, led to different options on how the simulation of the verification tests would be performed. The first option would be to let the author of the thesis use a copy of WUI-NITY, add the tests to the program and perform the simulation. The second option was to let the development team add the tests to the source code and run them, then provide the author with the simulated results for further use. The second option was opted in favour of having more time to focus on the analysis and discussion of the simulated results as well as adding improvements and modifications to the key factors and test templates. To compare the simulated results with expected results, hand-calculated results had to be made in using an available spreadsheet software. Having the simulation of the verification tests be performed by the development team, more time was also available to work on the validation testing. With a limitation on how much validation could be performed in the thesis for all components and functions surrounding pedestrian, traffic, and fire as well as their interaction with each other, keeping it as a simple validation for one component was deemed the best option. The focus was on the traffic component and needed to be at the core of the traffic model, being present in all simulations if possible. The useful component to perform the validation on was decided to be the relationships between speed and density, as well as flow and density. Necessary data to perform a validation on this component is also simple in regard to it only requiring a few traffic quantities that can be gathered from already existing traffic measurement systems.

The V&V workflow follows two iterative loops, one for verification testing and one for validation testing which comprise most of the performed work. In the iterative loop for verification testing, see Figure 1, the first step is to define the verification tests the software should be verified with. This included identify key factors, then put the key factors in to test templates and define an objective, draw geometrical boundary, present a scenario, describe what result is expected, what method is used and what actions the user needs to take for each of the key factors. After the test are defined, they are applied to the simulation software WUI-NITY. The verification tests were run automatically within the source code so that possibly newer versions of the code could be automatically tested. After WUI-NITY produces test results they are compared to expected hand-calculated results and the differences are analysed. While the tests are hard-coded in the source of the tool, the expected results of the tests are produced through separate hand-calculations, i.e., the expected result is not hard-coded in the source. Through the analyse of the result, improvements to the tests can be made, e.g., additions of sub-cases, simplified geometries, other scenarios, new tests with interactions to additional modelling layers. With improvements made to the verification tests they are run again, and the new results are analysed once more. From here the iterative loop continues.

In the iterative loop for validation testing, see Figure 2, the first step is to define the case study to be used. This needs to be a well-documented real-life scenario or experimental data. The case study should include detailed data related to the testing to be performed with the simulation software. This can be sourced from an appropriate data source or database, e.g., a traffic data measurement system. Once the data source is selected, what type of data to be extracted needs to be defined. Considering the example of the fundamental traffic flow relationships, quantities such as speed, flow and density are useful to extract, among other aspects like time of day and traffic incidents. The extracted data may have been measured in specific units, so they may need to be converted, normalized, or re-calculated to get appropriate units that then have potential to be included in a fundamental diagram. Some data could have been measured with low quality measurements or incidents occurring during the measurements. Such issues can cause the measured data to not represent the actual traffic dynamics that usually occur naturally and need to be discarded if the impact on the traffic data can be clearly observed. The measured data not affected by these external factors can become part of the constructed fundamental diagrams that represents the evacuation traffic and the routine non-emergency traffic. The created fundamental diagrams based on the measured traffic data during a real-life scenario is then compared to theoretical fundamental diagram implemented in the simulation software to see if the theoretical data accurately represents the gathered data and can re-produce the results from the event. To improve the validation, new data can be gathered and analysed again to provide additional detailed data for a more complete fundamental diagram. The results gathered from the validation can be used as a basis for what underlying assumptions made in WUI-NITY can be changed and improved on. A similar approach can be used for all different variables and functionalities included in the simulators that need to be tested.

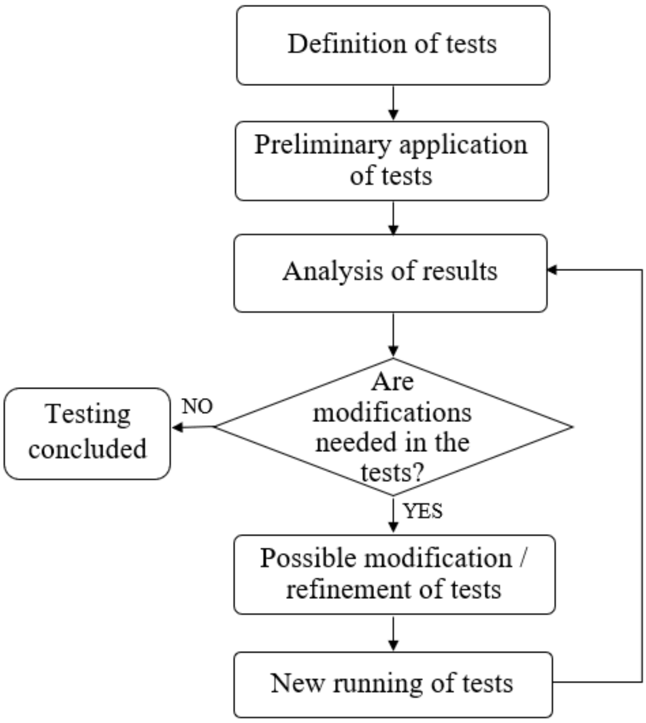


Figure 1 - Iterative loop of workflow verification testing

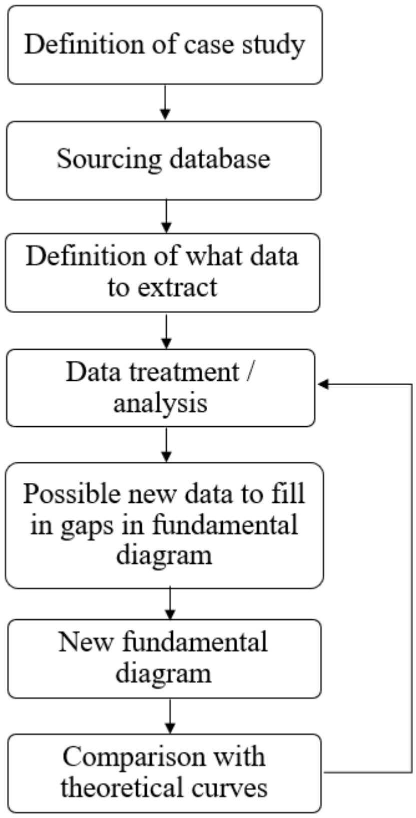


Figure 2 - Iterative loop of workflow for validation testing

4. Verification testing for WUI fire traffic evacuation models

The process of verification and validation is an important step when making sure that the results produced by simulation models are reliable and the simulation models' most suitable field of application gets defined. The definition of verification is "*process of determining that a calculation method implementation accurately represents the developer's conceptual description of the calculation method and the solution to the calculation method*" (ISO/TC 92/SC 4, 2015). When using calculation models in simulators, it is important that the calculation shows accurate enough predictions of components and functions and that the calculations are validated to be able to re-produce fire-and evacuation events. This grants the calculation and simulation models credibility and becomes trustworthy for those who will have use of the models (ISO/TC 92/SC 4, 2015).

The main guidelines available how to perform verification and validation on evacuation models are provided by the International Maritime Organization (IMO), in their report *Guidelines for evacuation analysis for new and existing passenger ships,* the MSC/Circ.1238. In this report the IMO list four main categories of tests that must be performed for developed evacuation models. Those are 1) component testing, 2) functional verification, 3) qualitative verification 4) quantitative verification. Component testing is a procedure to check that the different components of the software or model perform as intended. Functional verification concerns controlling that the model have the intended abilities to show the range of capabilities needed to perform the simulations. Qualitative verification involves the nature of predicted human behaviour with informed expectations. Quantitative verification concerns comparing model predictions against reliable experimental data. The guidelines do not provide with additional information and examples of tests to perform for quantitative verification because a lack of reliable data. (International Maritime Organization, 2007)

The tests are constructed following a structure used by ISO (ISO/TC 92/SC 4, 2020) consisting of six parts: 1) *Objective:* description of what component or behavior is being tested and what model/method it is being compared against to ensure the parameter is functioning properly, 2) *Geometry*: the configuration of the test, 3) *Scenario(s)*: the evacuation scenario that is going to be simulated, 4) *Expected result*: the result (qualitative or quantitative) that the evacuation model is supposed to produce 5) *Test method:* the qualitative (e.g., visualization of the represented behavior) or quantitative (e.g. comparison of evacuation times, flows, etc.) method employed for the comparison between the expected result and the simulation results, and 6) *User's actions*: the actions required of the tester while performing and presenting the tests. (Ronchi, et al., 2013)

When presenting tests suggested for verification of evacuation models, the test should be organized in elements which is considered necessary to meet the most basic representation of a scenario. These five core components of evacuation models are 1) pre-evacuation, 2, movement and navigation, 3) exit usage, 4) route availability and 5) flow conditions/constraints. They are hypothetical ideal tests that are designed to analyze the main features of evacuation models. The tests can be separated into two groups, analytical verification, and verification of emergent behaviors. The analytical verification refers to components with expected results that can be derived from mathematical calculations or evidence. The verification of emergent behavior refers to the evacuation model's capabilities to reproduce human behavior in a fire evacuation qualitatively based on current knowledge through the simulation results. The verification tests concerning emergent behavior are not labeled here as validation, since there are more in line with behavior theory rather than quantitative use of experiments or collected evacuation data. (Ronchi, et al., 2013)

4.1. Verification testing for WUI fire evacuation models

This section presents the suggested factors for consideration in the verification testing of WUI evacuation, with a main focus on the traffic modelling component. They are organized using the five core components in evacuation models (ISO/TC 92/SC 4, 2020) as a starting point, while adding and removing categories suitable for the tests. The tests were defined together with the international team taking part in the project "WUI-NITY2: the integration, verification, and validation of the wildfire evacuation platform WUI-NITY".

Category	Variable	Test code
Pre-evacuation (response)		
	Pedestrian re-distribution	P.1
	Response curve	P.3
Movement and navigation		
	Uni-directional single vehicle flow (one road type)	T.1a
	Uni-directional single vehicle flow (multiple road types)	T.1b
	Background traffic	T.2
	Relationship between speed-density and flow-density	T.4
	Group evacuation	T.7
	Lane changing/overtaking	T.8
	Acceleration/deceleration	T.9
	Intersection	T.11
	Vehicle demand vs arrival distribution	T.15
En route selection		
	Forced destination	T.12
	Destination choice in traffic	T.13
	Route choice in traffic	T.14
Flow condition/constraints		
	Change in carriageway configuration	T.3
	Flow at destination	T.6
Population		
	Max vehicles per household	P.2
	Pedestrian walking speed	P.4
	Pedestrian distance to vehicle	PT.1
Events		
	Vehicle speed reduction in reduced visibility conditions	T.5
	Road accident	T.10
	Route loss	WT.1
	Lane reversal	WT.2
	Loss of shelter or exit	WT.3
	Refuge capacity	WT.4

Table 1 - Initial factors for verification, covering category, variable and test code.

4.2. Key Factors included for verification testing

This section presents the key factors that need to be considered for a WUI fire evacuation model. The description of the factors will contain information on how they are defined, and what they are testing. Many of the factors carries similarities from factors in V&V testing for fire evacuation in buildings, but instead of using people and buildings, the factors are modified or adapted to be applicable for vehicles and road networks (Ronchi, 2020). In addition, since there is no currently existing verification testing standardized protocol for macroscopic traffic evacuation models used in the WUI context, suggestions for new factors to test are included what revolves around the pedestrian, traffic and wildfire layers and interactions between the layers.

Pedestrian re-distribution

The map used to perform evacuation simulation contains a traffic network and households with a grid system to divide the map into sections. If households in a section cannot connect to the traffic network through a traffic node, they need to re-distributed so they can access the traffic network.

Max vehicles per household

The number of vehicles a household have access to and uses in an evacuation varies. The more vehicles used the more belongings and necessary supplies can be taken with until the household members can return. The assumptions of number of vehicles available at each household should be tested with a probability to take additional vehicles.

Response curve

The response curve represents the time it takes for people to pick up on cues from an approaching wildfire and start evacuating. Cues can be smoke from wildfire, neighbourhood activity, radio messages, evacuation order etc (Folk, et al., 2019). People can start evacuating before evacuation orders are issued, delay their evacuation, or not evacuate at all.

Pedestrian walking speed

The pedestrian walking speed checks that a pedestrian can walk from its starting location to a destination to either reach safety or a traffic node to evacuate the area with an assigned walking speed. The walking speed may vary between people, some pedestrian adapts a slower walking speed than what is considered normal (Gwynne & Boyce, 2016).

Pedestrian distance to vehicle

The pedestrian walking distance variable investigates that a pedestrian can walk from its starting location to a destination to either reach safety or a traffic node to evacuate the area. The walking distance varies between pedestrians, some are further away from the access to the traffic system or must move around obstacles and adapt a higher walking distance than others.

Uni-directional single vehicle flow

Each road type has a corresponding speed limit which can be adopted by vehicles driving at free flow speed. The vehicle flow should only be open in one direct on the road. The free flow speed should change if the vehicle enters another road type with a different corresponding speed limit.

Background traffic

The background traffic represents vehicles present on a road which are not actively evacuating. This type of traffic affects the vehicles density modifier which reduces the free flow speed for all vehicles since the road becomes more occupied and slower driving behaviour is adapted to the new traffic circumstances.

Change in carriageway configuration

Change in carriageway configuration refers to how many lanes on the carriageway are accessible. Going from one lane to two lanes increases the traffic capacity and all vehicles can adapt a higher free flow speed. In the case of going from two lanes to one lane means all vehicles must adapt a lower free flow speed.

Relationships between speed-density and flow-density

The so called "fundamental diagrams" represent the speed-density and flow-density relationships which with increase in traffic density change the speed and flow of the traffic. The speed is generally reduced with increases in density, while the flow increases with increasing density to a point where maximum flow (often referred in the pedestrian movement literature as capacity drop (Seyfried, et al., 2005)) is reached and then the flow reduces with increasing density.

Vehicle speed reduction in reduced visibility conditions

Traffic evacuation through a wildfire area can have large amount of smoke obscuring the view for the vehicles making it unsafe to drive at the usual adapted speeds for that specific road type. This causes the adapted speeds to be decreased with decreasing visibility conditions, in addition to the potential speed reduction already adapted for increasing traffic densities (Wetterberg, et al., 2021).

Flow at destination

The area an evacuation is taking place at usually have destinations or exits for leaving the area where evacuees can be considered safe. The flows at these destinations should not exceed a maximum flow rate when vehicles arrive at the destinations and the remaining traffic density is reduced and speed and flow increases. The flow rate should get reduced or remain the same.

Group evacuation

Group evacuation with friends and family can be present if the members of a household (or more than one household) take multiple vehicles with the goal of evacuating close together in the traffic evacuation. Multiple vehicles staying together in the traffic flow can be difficult with the presence of surrounding traffic, but the vehicles should be leaving the household at about same time.

Lane changing/overtaking

In traffic, the speed people chose to drive at for specific road types varies between people. They can have different vehicles, driving experience, personal behaviours etc. with naturally makes people drive differently (Gray & Regan, 2015). This difference in speed can cause the faster driving vehicles to change lanes and overtake to keep their current driving speed.

Acceleration/deceleration

Acceleration and deceleration of vehicles may happen in traffic evacuation in response to surrounding traffic or approaching intersection or roundabout (Xu, et al., 2010). Even without changes in surrounding traffic or upcoming intersections vehicles can change their speed due to events happening inside the car or the road is having an incline.

Road accident

Road accidents can happen anytime in traffic evacuations. With the short duration of increase in traffic density and an overhanging emergency, there are more vehicles that can become part of a road accident. The road accident could cause certain lanes to be blocked or stopping the traffic flow completely, and the accident can also be resolved.

Intersection

Intersections where two or more roads meet each other, can be signalized or unsignalized in how it handles the traffic evacuation flow (Parr, et al., 2016). Other type of intersection can be roundabouts which handles many flows at the same time. The intersections can also be on- and off-ramps to highways, where the flows merge or disperse.

Forced Destination

When deciding what destination to head for in an evacuation, the destination may not always be the closest or fastest one, but one further away because of errands that need to be handled before evacuating, such as picking up family members not present in the household, all other roads are closed, familiarity with a given destination, etc. (Akbarzadeh & Wilmot, 2015). Forced destination is an override to usually applied destination choices.

Destination choice in traffic

Destination choice refers to the evacuees' decision on what destination to drive towards. The decision can be based on the shortest route to a destination, fastest route, or a specified route to another destination. Other conditions can also be present that affects the decision making, such as presence of smoke (Wetterberg, et al., 2021) or familiarity (Akbarzadeh & Wilmot, 2015).

Route choice in traffic

Route choice in traffic refer to the evacuee's decision on what route to take to reach a destination. The decision making can be based on if the route is faster or shorter but can also be affected by other conditions such as route familiarity (Intini, et al., 2019), smoke blocking or impeding a route (Wetterberg, et al., 2021), etc.

Vehicle demand vs arrival distribution

Vehicle demand vs arrival distribution refers to the how many vehicles leave the starting point of the road network and how many arrive at the destination in the road network. The number of vehicles starting evacuation should be the same number of vehicles that reaches the destination and managed to evacuate. Vehicles can break down or get stuck along the way.

Route loss

Route loss refers to when a road section is no longer available of use to the traffic evacuation. When a route is closed other routes need to be used for the remaining traffic to evacuate. Reasons the route is closed can be that the wildfire has approached and is raging close to the road, making it unsafe to use.

Lane reversal

Lane reversal is an option that can be implemented on roads with larger capacity and lanes by officials to increase the number of lanes open in the evacuation direction. This also means that the number of lanes for emergency personal and others are reduced. The increase of capacity the lane reversal function provides helps increase traffic flow and reduce evacuation times. (Akbarzadeh & Wilmot, 2015)

Loss of exit or shelter

Loss of exit or shelter refers to when a destination the evacuation traffic is heading towards is no longer available of use for additional traffic. Reasons the exit is closed can be that the wildfire is blocking access to the destination and the remaining traffic needs to be redirected to another destination.

Refuge capacity

Refuge capacity refers to the amount of people that can fit in an emergency shelter. When a shelter has reached maximum capacity no more people can fit in the shelter and newcomers need to find another shelter. The notification of a shelter being full can be announced by sight when newcomers arrive or by radio to not waste precious time driving back and forth.

4.3. Application of Verification testing to WUI-NITY

The verification tests are built in WUI-NITY designing hypothetical simple scenarios in OpenStreetMap. To build those, JOSM[1] was used, which is a free software editing tool for OpenStreetMap geodata created in Java.

Here there is an initial list of verification scenarios for WUI-NITY. At the moment those are grouped in relation to the type of layer they cover (pedestrian, traffic or integration with wildfire). At this stage, the number of tests is deliberately limited to a manageable and reasonable size to not have too many tests at this early stage of development. Annex A presents a reporting template to present the results.

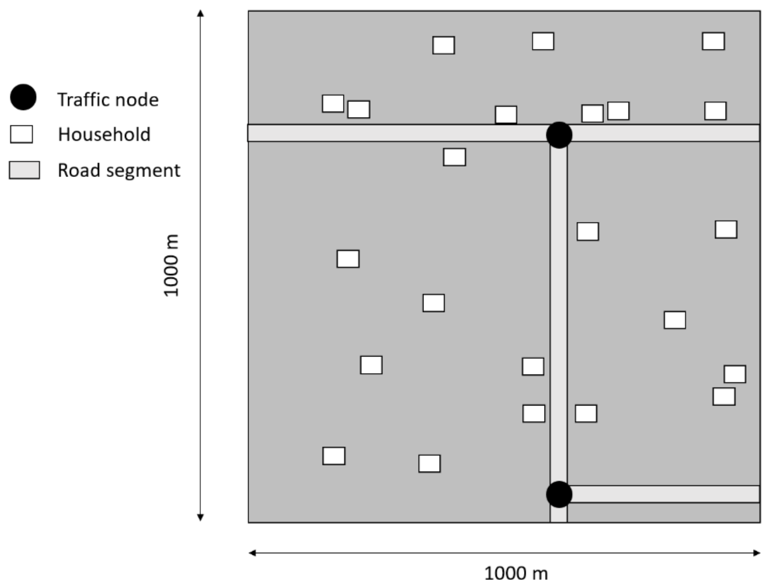
Layer tested	Core component	Test code	Test title	Sub-tests	Conducted test
Pedestrian	Population	P.1	Pedestrian re-distribution	/	NO
Pedestrian	Population	P.2	Max vehicles per household	/	NO

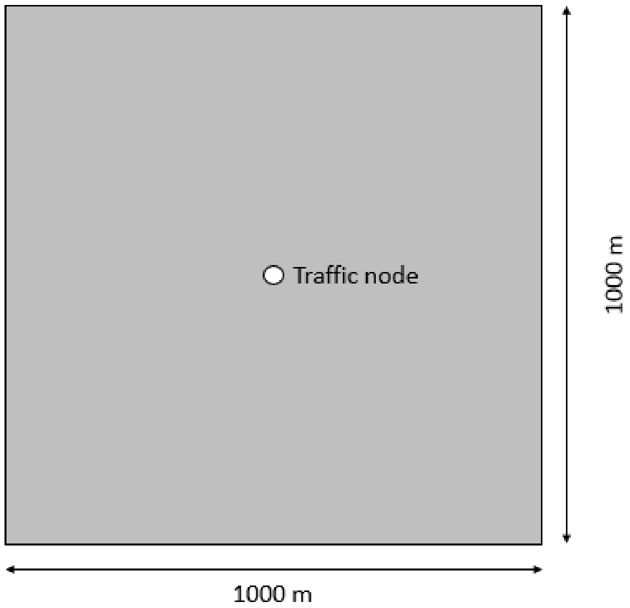
[1] https://josm.openstreetmap.de/

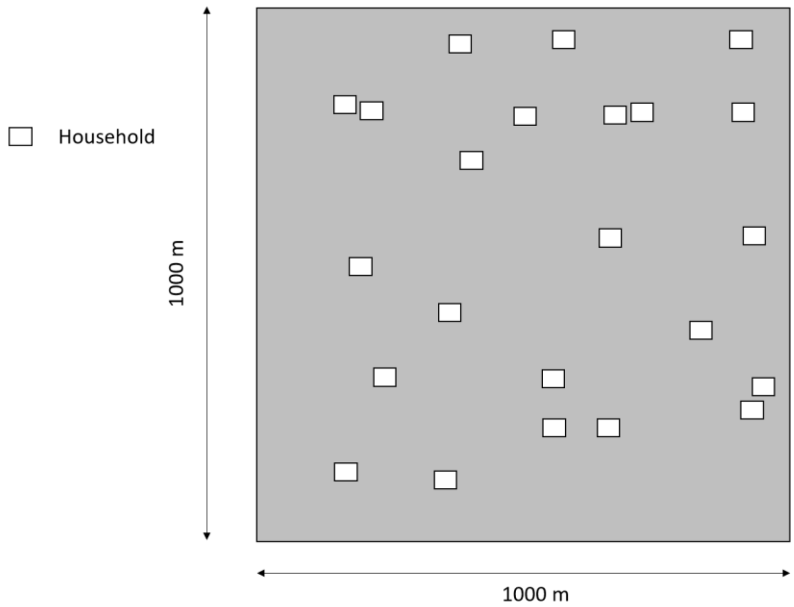
Pedestrian	Pre-evacuation	P.3	Response curve	Default, linear and custom response curve	NO
Pedestrian	Movement	P.4	Pedestrian walking speed	2 values of walking speeds (based on multipliers)	NO
Integration Pedestrian+Traffic	Movement	PT.1	Pedestrian distance to vehicle	2 values of walking speeds (based on multipliers)	NO
Traffic	Movement	T.1	Uni-directional single vehicle flow	T.1a: One road type T.1b: Multiple road types	YES
Traffic	Movement, Flow constraints	T.2	Background traffic	/	YES
Traffic	Movement	T.3	Change in carriageway configuration	5 vehicle density levels (linearly from 0 veh/km/lane to the vehicle density leading to stop)	YES
Traffic	Movement, Flow constraints	T.4	Relationships between speed-density and flow-density	5 vehicle density levels linearly ranging from 0 veh/km/lane to the vehicle density corresponding to a congested scenario	YES
Traffic	Movement, Flow constraints	T.5	Vehicle speed reduction in reduced visibility conditions	5 vehicle density levels linearly ranging from 0 veh/km/lane to the vehicle density corresponding to a congested scenario and give visibility values (optical density per m of 0.05 m^{-1}, 0.10 m^{-1}, 0.15 $m^{-1}$and 0.20 m^{-1})	YES
Traffic	Movement, Flow constraints	T.6	Flow at destination	5 vehicle density levels linearly ranging from 0 veh/km/lane to the vehicle density corresponding to a congested scenario	YES
Traffic	Movement, Route selection	T.7	Group evacuation	Two density levels (no initial density and density corresponding to 50% of road capacity)	NO

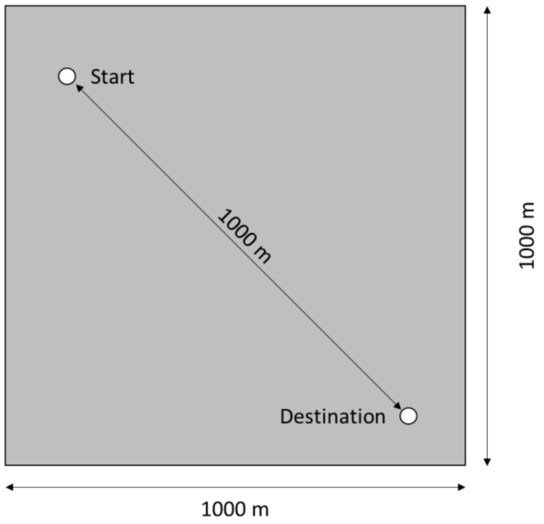
Traffic	Movement, Flow constraints	T.8	Lane changing / overtaking	/	NO
Traffic	Movement, Flow constraints	T.9	Acceleration / deceleration	/	NO
Traffic	Movement, Flow constraints, Event	T.10	Road accident	/	YES
Traffic	Movement, Flow constraints	T.11	Intersection	/	YES
Traffic	Route selection	T.12	Forced Destination	/	YES
Traffic	Route selection	T.13	Destination choice in traffic	Each route choice method (fastest, closest, other condition)	YES
Traffic	Route selection	T14	Route choice in traffic	Each route choice method (fastest, closest, other condition)	YES
Traffic	Movement, Flow constraints	T.15	Vehicle demand vs arrival distribution	Different numbers of vehicles	YES
Integration Wildfire + Traffic	Route selection	WT.1	Route loss	/	NO
Integration Wildfire+Traffic	Movement, Events	WT.2	Lane reversal	/	YES
Integration Wildfire + Traffic	Movement, Flow constraints, Event	WT.3	Loss of exit or shelter	/	YES
Integration Wildfire + Traffic	Movement, Flow constraints, Event	WT.4	Refuge capacity	/	YES

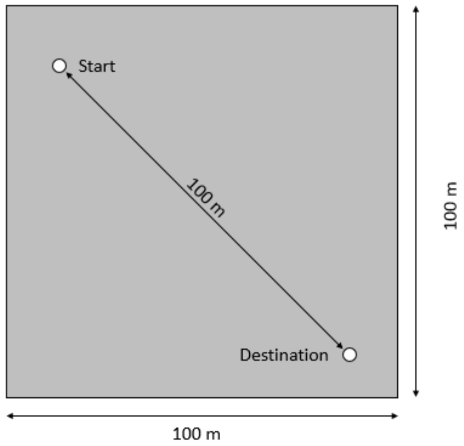
Table 2 - Initial list of verification scenarios, covering layer tested, core component, test code, test title, sub-tests and if test was conducted.

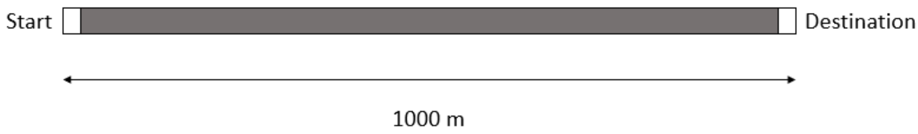
P.1	**Pedestrian re-distribution**
Objective	Assess consistency between the conceptual and implemented re-distribution of pedestrians in space based on available routes
Geometry	A walkable area of 1000 m * 1000 m including a set of households. 50% of those households have access to a node of the road network, the rest does not have access (the figure below shows an example). 
Scenario(s)	Let the simulator re-distribute people in the households based on the algorithm adopted by the model, so that all population can access a node of the road network.
Expected result	All population should be able to access the road network and the number of people accessing the road network should correspond to the number of people implemented in the scenario.
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the population re-distribution should be reported.

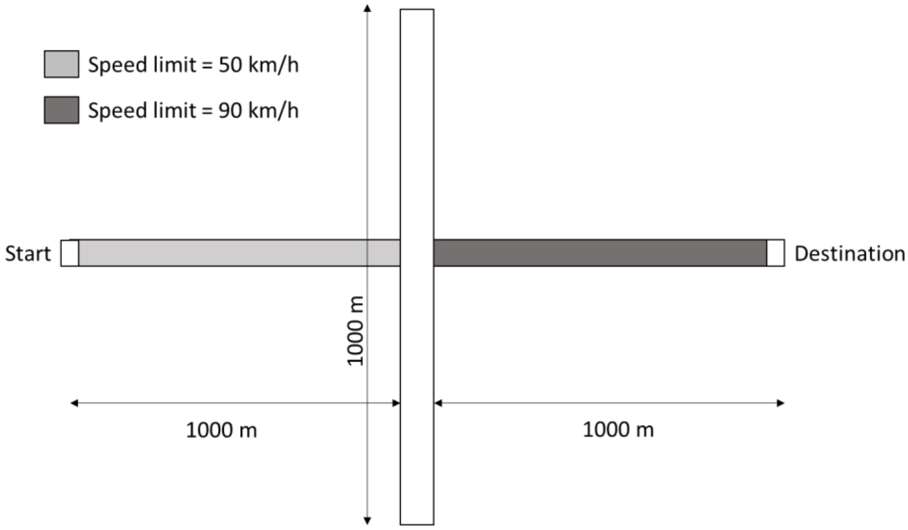
P.2	**Max vehicles per household**
Objective	Assess consistency between implemented relationship for number of cars distributed to each household and hand-calculated results.
Geometry	A walkable area considering movement to a traffic node. 
Scenario(s)	A given group of pedestrians leave their households with an assigned movement speed of 1 m/s and a response time equal to 0 moving along the walkable area to the traffic node. Each household should have 1-5 cars available given predetermined values. While running the test case, the user should turn off any non-relevant models, except the pedestrian simulation model.
Expected result	The number of vehicles entering the traffic model should correspond to the implemented numbers of vehicles assigned to each household with its probability distribution for additional vehicles (to be calculated in accordance with the modelling assumptions adopted).
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the pedestrian exhibits acceleration/deceleration during the movement.

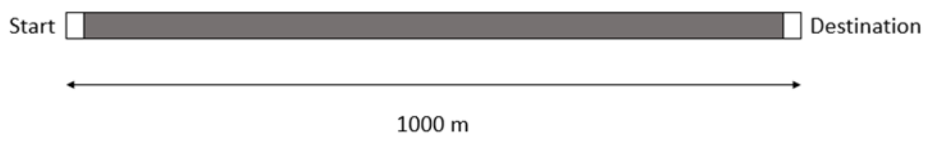
P.3	Response curve
Objective	Assess consistency between implemented pedestrian response model and hand-calculated results. This includes comparing the number of pedestrians that evacuate before the evacuation alarm, after the alarm and those who do not evacuate.
Geometry	A walkable area of 1000 m * 1000 m, which includes a set of (sufficiently large) households defined by the user. 
Scenario(s)	A given group of pedestrians leave their households with a distributed response time drawn from the default response curve. Repeat the test using a custom response curve for the pedestrians on the walkable area (e.g. using a linear or custom response curve, starting on X-axis < 0). While running the test case, the user should turn off any non-relevant models, except the pedestrian response model.
Expected result	The pedestrians should leave their households in accordance with the expected time and the % of people evacuating before the trigger, after the trigger and those who do not evacuate should correspond to the pre-defined response curve (to be calculated in accordance with the modelling assumptions adopted).
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The test should be repeated for each distribution type included in the model.

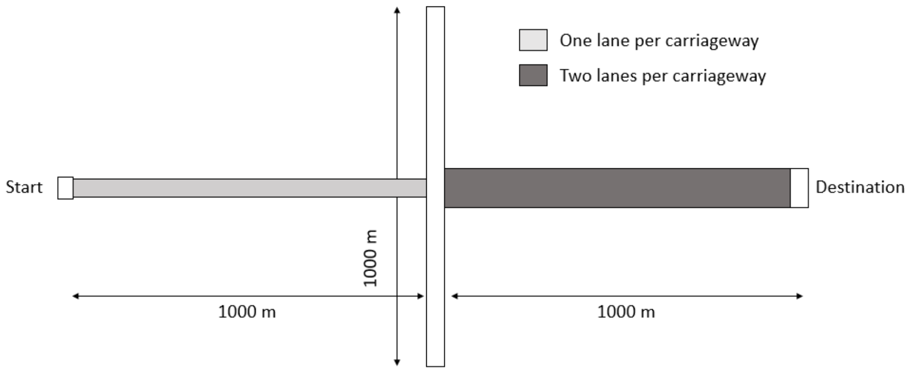
P.4	Pedestrian walking speed
Objective	Assess consistency between the conceptual and implemented relationship concerning pedestrian movement based on walking speeds.
Geometry	A walkable area of 1000 m * 1000 m considering movement for a total length of 1000 m and assuming no obstacles along the path. The walkable area should correspond to a speed limit equal to 1 m/s. 
Scenario(s)	One pedestrian with an assigned movement speed of 1 m/s and a response time equal to 0 s moving along the walkable area (from start to destination), with a given speed multiplier. Repeat the test varying the speed multiplier of pedestrian walking speed on the walkable area (e.g., using 2 different values of speed multipliers from no multiplier (=1) to a multiplier that corresponds to a pedestrian that adopts a slower walking speed (< 1)). While running the test case, the user should turn off any non-relevant models, except the pedestrian simulation model.
Expected result	The pedestrian should cover the distance to the traffic node in expected time (to be calculated in accordance with the modelling assumptions adopted).
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the pedestrian exhibits acceleration/deceleration during the movement.

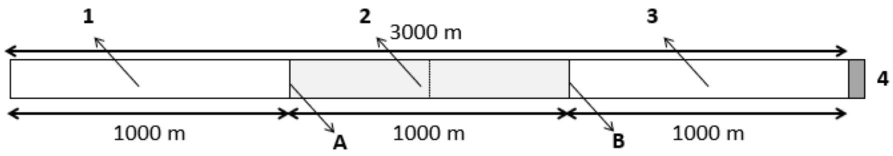
PT.1	**Pedestrian distance to vehicle**
Objective	Assess consistency between implemented relationship between pedestrian distance and hand-calculated results.
Geometry	A walkable area of 100 m * 100 m considering movement for a total length of 100 m. The walkable area should correspond to a speed limit equal 1 m/s. 
Scenario(s)	One pedestrian with an assigned movement speed of 1 m/s and a response time equal to 0 s moving along the walkable area (from start to destination), with a given distance multiplier. Repeat the test varying the distance multiplier of pedestrian distance on the walkable area (e.g., using 2 different values of distance multiplier from no multiplier (=1) to a multiplier that corresponds to a pedestrian taking a route with movement inefficiency (>1)). While running the test case, the user should turn off any non-relevant models, except the pedestrian simulation model and the traffic network.
Expected result	The pedestrian should cover the distance to the traffic node in expected time (to be calculated in accordance with the modelling assumptions adopted).
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the pedestrian exhibits acceleration/deceleration during the movement.

T1.a	**Uni-directional single vehicle flow (one road type)**
Objective	Assess consistency between speed assignment of one vehicle on a single road type and model representation for uni-directional movement.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). Repeat the test changing the road type to correspond to a speed limit on the lower end (e.g. 30 km/h) as well as a speed limit on the higher end (e.g. 120 km/h). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

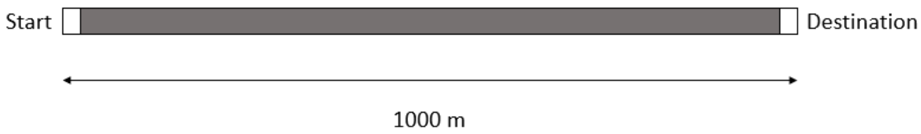
T.1b	**Uni-directional single vehicle flow (multiple road types)**
Objective	Assess consistency between speed assignment of one vehicle on multiple road types and model representation for uni-directional movement.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m + 1000 m (see Figure below) with an unsignalized intersection (the user can choose the length of the intersecting road, in this example this is equal to 1000 m). The first part includes a road type corresponding to a speed limit equal to 50 km/h, the second part a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limits (50 km/h and 90 km/h) moving along the road (from start to destination). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

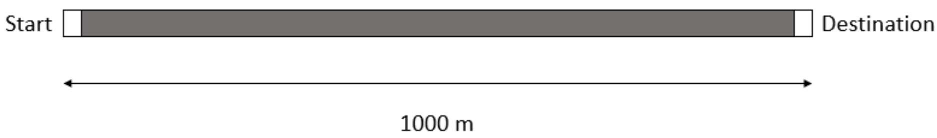
T.2	**Background traffic**
Objective	Ensure the impact of background traffic on vehicle flow is correctly implemented.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). A background traffic reducing the flow capacity of the road of 50% is implemented. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

T.3	**Change in carriageway configuration**
Objective	Assess consistency between the implemented impact of change in carriageway configuration and calculated one for uni-directional movement.
Geometry	A road with a single carriageway for a total length of 1000 m + 1000 m (see Figure below) with an unsignalized intersection (the user can choose the length of the intersecting road, in this example this is equal to 1000 m) is considered. The initial 1000 m segment of the road has one lane per carriageway, while the following 1000 m segment has two lanes per carriageway. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). Repeat the test varying the initial density of vehicle on the road (e.g. using 5 vehicle density levels linearly from 1 veh/km/lane to the vehicle density corresponding to the vehicle being stopped considering the portion of the road with smaller capacity). The associated speed limit in the two road segments changes accordingly. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

T.4	**Relationships between speed-density and flow-density**
Objective	Assess qualitative consistency between the implemented relationships between traffic flow/density and speed/density in a road segment and simulated one considering uni-directional movement.
Geometry	A road segment is represented with a single carriageway considering movement on a single lane for a total length of 3000 m divided in three zones of equal length (see Figure below, drawing is off scale). The road type should correspond to a speed limit equal to 70 km/h. The road segment is divided in three zones, namely zone 1 (white), zone 2 (light grey) and zone 3 (white). 
Scenario(s)	Calculate 5 vehicle density levels linearly ranging from 1 veh/km/lane to the vehicle density corresponding to a congested scenario (Density 1=D1=1 veh/km/lane, D2, D3, D4 and D5=density leading to stopped vehicles on the road segment). The vehicles are uniformly distributed in the entire road segment (zone 1, 2 and 3). They have an initial free flow speed equal to the speed limit. Step 1: Assign a number of vehicles corresponding to the D3 vehicle density on the road segment to move to the right towards the destination of the road segment. Place the last vehicle in zone 2 near line A and measure the time that it takes from line A to line B and estimate the associated driving speed. Measure the average vehicle flows in line B (with a time interval decided by the tester) starting from the beginning of the simulation until the last vehicle in zone 2 arrives to Line B. Vehicle densities in zone 2 are recorded when the last vehicle in zone 2 reaches the centre of zone 2. Step 2: Step one is repeated with D1, D2, D4 and D5. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The relationship between driving speeds and vehicle densities in zone 2 as well as the flows in line A vs vehicle densities in zone 2 are plotted and compared with the underlying assumptions used in the traffic evacuation model.
Test method	The test method is a qualitative verification of the vehicle movement.
User’s actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order

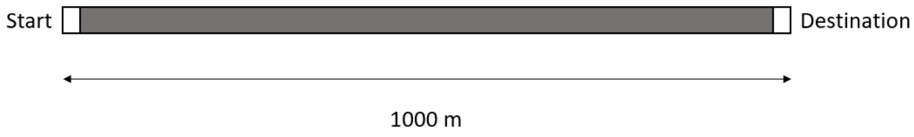
	to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement. The tester may also show results in relation to different time intervals adopted for the estimation of flows, people densities and walking speeds.

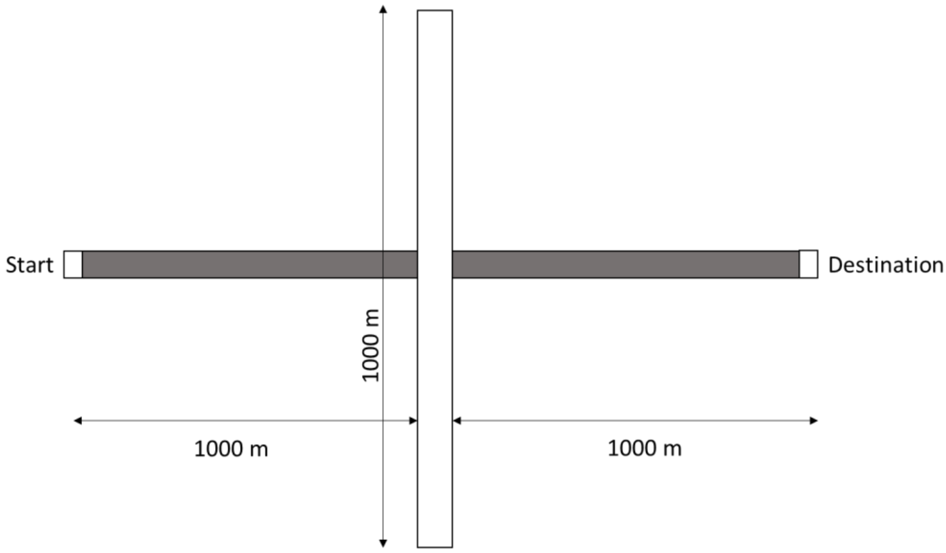
T.5	Vehicle speed reduction in reduced visibility conditions
Objective	Assess consistency between implemented relationship between reduced speed due to smoke and hand-calculated results.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 70 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (70 km/h) moving along the road (from start to destination), with a given set visibility value. Repeat the test varying the initial density of vehicle on the road (e.g. using 5 vehicle density levels linearly ranging from 1 veh/km/lane to the vehicle density corresponding to a congested scenario) and five visibility values (no smoke, and four different levels of visibility, e.g. visibility corresponding to an optical density per m of 0.05 m^{-1}, 0.10 m^{-1}, 0.15 $m^{-1}$and 0.20 m^{-1}). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User’s actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

T.6	Flow at destination
Objective	Assess consistency between maximum flow rates at destination and model representation.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	Calculate 5 vehicle density levels linearly ranging from 1 veh/km/lane to the vehicle density corresponding to a congested scenario (Density 1=D1=1 veh/km/lane, D2, D3, D4 and D5=density leading to stopped vehicles on the road segment). The vehicles are uniformly distributed in the entire road segment. They have an initial free flow speed equal to the speed limit. Step 1: Assign a number of vehicles corresponding to the D3 vehicle density on the road segment to move to the right towards the destination of the road segment. Step 2: Step one is repeated with D1, D2, D4 and D5. While running the test case, the user should turn off all the non-relevant modelling layers, except the traffic simulation model. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The flow rate at the destination over the entire period should not exceed a pre-defined maximum threshold.
Test method	The test method is a quantitative evaluation of model results, i.e. the comparison between the results produced by the model and the maximum flow rate.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. If the model represents flows as an emergent property, the maximum flow rate for the test should be defined

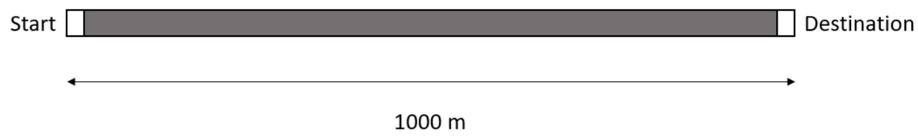
	by the tester in relation to the underlying assumptions used during the development of the model. The model tester should document the assumptions adopted in the representation of the flows (emergent flow or user-defined).

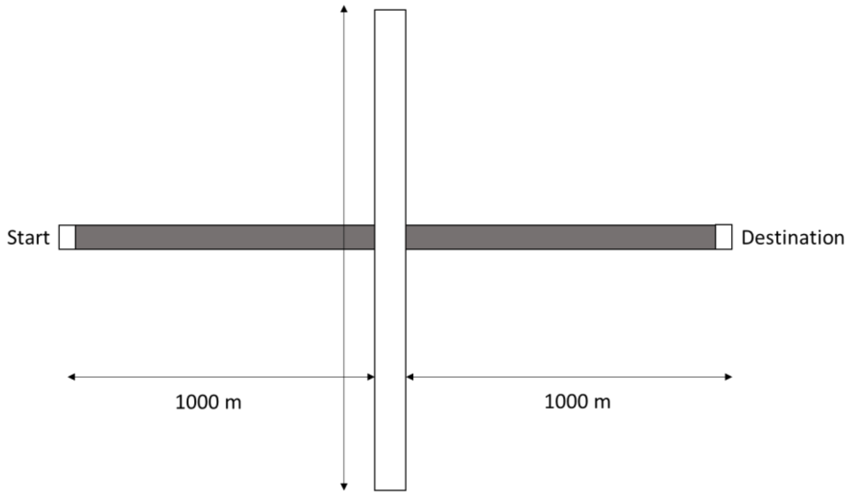
T.7	**Group evacuation**
Objective	Assess consistency between the conceptual representation of group evacuation of vehicles leaving the same household and the modelled representation of group evacuation.
Geometry	A road with a single carriageway considering movement on a single lane with a starting point off-centre leading to two destinations for a total length of either 1000 m or 2000 m (see Figure below). The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	More than one vehicle leaves the household with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination B). Two sub-cases are conducted, one without any initial density on the road and one with an initial density of vehicles corresponding to 50 % of the capacity of the road. The vehicles leave the start location at the same time. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicles should take the same route to the destination and cover the distance of the road in approximately the same expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

T.8	Lane changing/overtaking
Objective	Assess consistency between conceptual vehicles capabilities to overtake on a single road type and modelled representation of overtaking.
Geometry	A road with a single carriageway (two lanes per direction of movement for a total of four lanes) considering movement for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle starts with an assigned movement speed that is lower than the free flow speed moving along the road (from start to destination). Another vehicle is injected right after the first vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The faster vehicle should overtake the slowest vehicle and cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

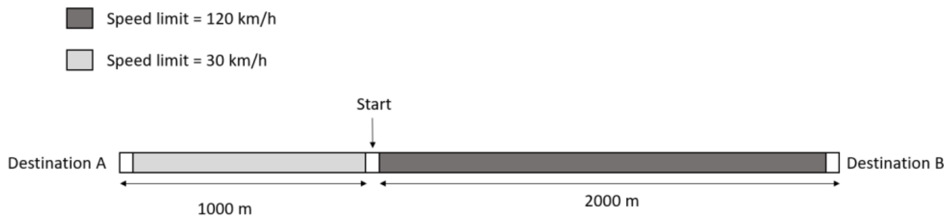
T.9	Acceleration/deceleration
Objective	Assess consistency between acceleration and deceleration for speed assignment of one vehicle on a single road type and model representation for acceleration and deceleration.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m + 1000 m (see Figure below) with an intersection (the user can choose the length of the intersecting road; in this example this is equal to 1000 m). The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination) stopping at the intersection. Repeat the test removing the intersection from the road. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time for both tests (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order

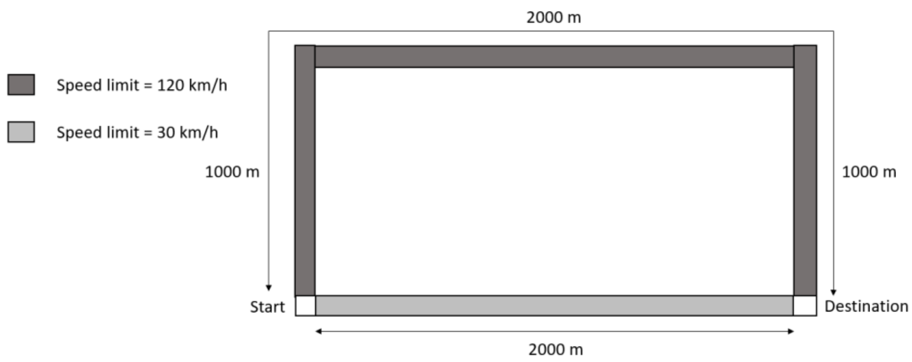
	to test the sensitivity of the results to cell size. The method for setting up the destination should be reported.

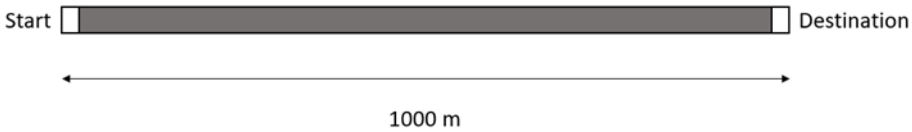
T.10	Road accident
Objective	Assess the impact of road accident on traffic flow by checking consistency between the simulated evacuation time for one vehicle with a speed assignment on a single road type and model representation for road accidents. This is aimed at predicting the link response in case of crash (i.e., how the flow changes).
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). After 10 s in the simulation, an event is triggered, and the road accident is implemented in the road segment leading towards the Destination. Two sub-cases are conducted, one which changes the free-flow speed to stall speed > 0 after the implementation of the road accident, for the remaining duration of the test. The other changes the free-flow speed to stall speed equal to 0 for the remaining duration of the test. A time limitation is needed to prevent infinite simulation time. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

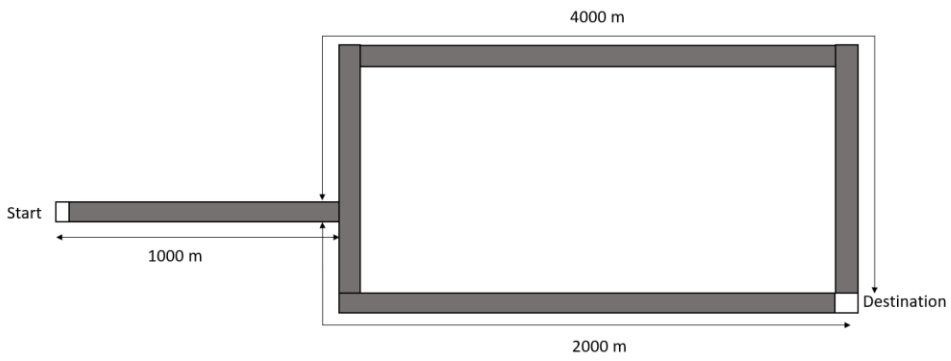
T.11	Intersection
Objective	Assess consistency between speed assignment of one vehicle on multiple road segments and model representation for unsignalized intersections.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m + 1000 m (see Figure below) with an unsignalized intersection (the user can choose the length of the intersecting road, in this example this is equal to 1000 m). The road type before and after the intersection should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

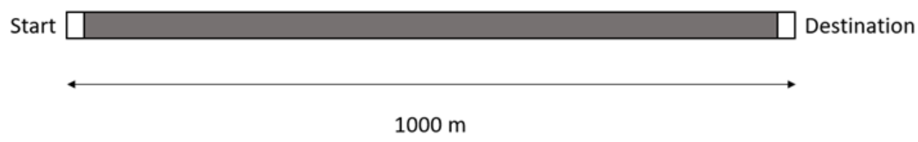
T.12	**Forced Destination**
Objective	Assess consistency between the conceptual implementation of a forced destination and the model representation of a forced destination.
Geometry	A road with a single carriageway considering movement on a single lane with a starting point off-centre leading to two destinations for a total length of either 1000 m or 2000 m (see Figure below). The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). The vehicle is forced to go towards Destination B through the implementation of a forced destination. If forced destinations cannot be implemented, the vehicle would by default drive towards Destination A since it is both the closest and fastest route. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance and drive to Destination B.
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. The method for setting up the destination should be reported.

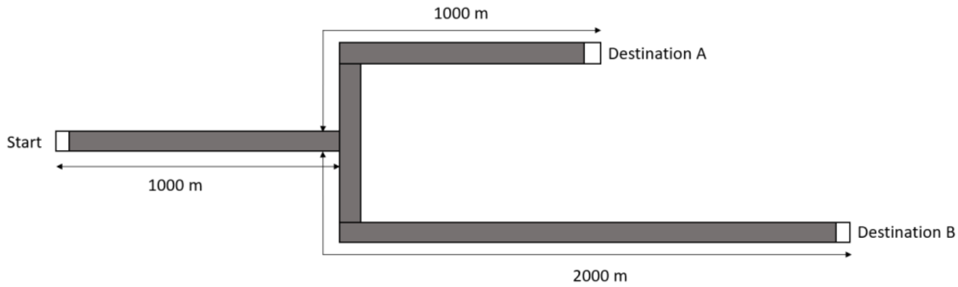
T.13	Destination choice in traffic
Objective	Assess consistency between the conceptual implementation of destination choice and model representation of destination choice.
Geometry	A road with a single carriageway considering movement on a single lane with a starting point off-centre leading to two destinations for a total length of either 1000 m or 2000 m (see Figure below). The road leading towards Destination A corresponds to a speed limit equal to 30 km/h for 1000 m. The road leading towards Destination B corresponds to a speed limit equal to 120 km/h for 2000 m. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limits (30 km/h and 120 km/h) moving along the road (from start to destination). Repeat the test for each destination choice method that is available (e.g. destination based on shortest route, fastest route, any other condition such as smoke that affects the selection). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should drive towards the correct destination that corresponds to the route choice made and cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

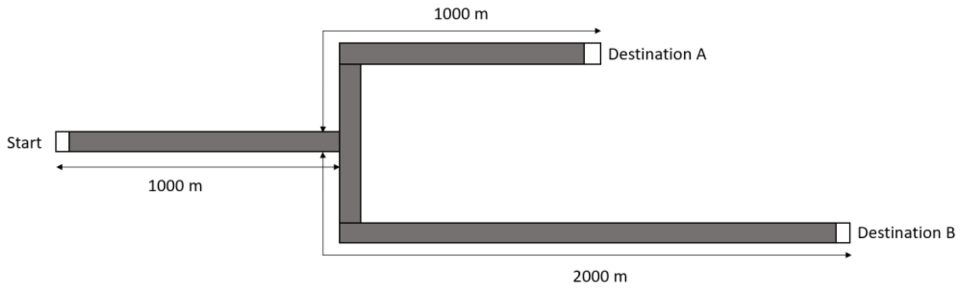
T.14	Route choice in traffic
Objective	Assess consistency between the conceptual implementation of destination choice and model representation of destination choice.
Geometry	A road with a single carriageway considering movement on a single lane with a starting point connecting two separate roads leading to the same destination for a total length of either 4000 m or 2000 m (see Figure below). The road type for the longer route should correspond to a speed limit equal to 120 km/h. The road type for the shorter route should correspond to a speed limit equal to 30 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limits (30 km/h and 120 km/h) moving along the road (from start to destination). Repeat the test for each destination choice method that is available (e.g. destination based on shortest route, fastest route, any other condition such as smoke that affects the selection). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should drive to the correct route that corresponds to the route choice made and cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User’s actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. The method for setting up the destination should be reported.

T.15	**Vehicle demand vs arrival distribution**
Objective	Assess consistency between implemented relationship for number of vehicles distributed in the traffic system and hand-calculated result.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	Implement given numbers of vehicles (2, 50, and 100) with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The number of vehicles reaching the destination should correspond to the implemented number of vehicles assigned to the traffic system (to be calculated in accordance with the modelling assumptions adopted).
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported.

WT.1	**Route loss**
Objective	Assess consistency between the conceptual implementation of route loss (e.g., generated by the fire) and the model representation of route loss.
Geometry	A road with a single carriageway considering movement on a single lane with an intersection with two roads leading to the same destination for a total length of either 1000 m + 4000 m, or 1000 m + 2000 m (see Figure below). The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). After 10 s in the simulation (before the vehicle leaves the first segment), an event is triggered, and the 2000 m road before the Destination is closed. The vehicle would by default drive to the Destination the shorter route since it is both a closer and faster route. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should change its route after the event is implemented to the longer route, cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted, e.g. the time of the longer route)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. The method for setting up the destination should be reported. The user should also report the impact of the loss of route for the vehicles that are on the loss route on the moment when this is triggered.

WT.2	**Lane reversal**
Objective	Assess the impact of lane reversal (e.g. by increasing road capacity) by checking the consistency between the simulated evacuation time and the calculated one of a vehicle on a single road type with given traffic densities for uni-directional movement.
Geometry	A road with a single carriageway considering movement on a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). After 30 s in the simulation, an event is triggered and lane reversal is implemented in the entire road segment. Repeat the test varying the initial density of vehicle on the road (e.g., using 5 vehicle density levels linearly from 1 veh/km/lane to the vehicle density corresponding to the vehicle being stopped considering the portion of the road before the implementation of the lane reversal). While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should cover the distance of the road in the expected time (to be calculated in accordance with the modelling assumptions adopted)
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported. The model tester should also report if the vehicle exhibits acceleration/deceleration during the movement.

WT.3	**Loss of exit or shelter**
Objective	Assess consistency between the conceptual implementation of loss of exit/shelter and the model representation of loss of exit/shelter.
Geometry	A road with a single carriageway considering movement on a single lane with an intersection leading to two different destinations for a total length of either 1000 m + 1000 m, or 1000 m + 2000 m (see Figure below). The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	One vehicle with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). After 30 s in the simulation, an event is triggered, and Destination A is closed. The vehicle would by default drive towards Destination A since it is both a closer and faster route. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicle should change its destination after the event is implemented, cover the distance and drive to Destination B.
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User's actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. The method for setting up the destination should be reported. The user should also report the impact of the loss of exit/shelters on the vehicles that are closely approaching it.

WT.4	Refuge capacity
Objective	Ensure the impact of refuge reaching its full capacity and the re-direction of traffic to the next refuge is correctly implemented.
Geometry	A road with a single carriageway considering movement on a single lane with an intersection leading to two different destinations for a total length of either 1000 m + 1000 m, or 1000m + 2000 m (see Figure below). The road type should correspond to a speed limit equal to 90 km/h. 
Scenario(s)	Two vehicles with an assigned free flow speed corresponding to the speed limit (90 km/h) moving along the road (from start to destination). Both Destination A and B are refuges with capacity as emergency shelter for one person. The vehicles would by default drive towards Destination A since it is both a closer and faster route. While running the test case, the user should turn off any non-relevant models, except the traffic simulation model.
Expected result	The vehicles should cover the distance and drive to Destination A. When the first vehicle has reached the refuge and filled up its capacity, the second vehicle will change route and drive to Destination B.
Test method	The test method is a quantitative verification of model results, i.e. the difference between the expected result and the simulation results.
User’s actions	The effectiveness of this test can be improved by setting additional prescriptions in relation to the type of model under consideration. For example, in the case of models that use a network approach, results may be dependent on the configuration of the network/grid adopted. For grid-based models, considerations should also be made by the tester on the necessity of performing this test with different configurations (e.g. simulating the default cell size and a set of both reduced and increased cell sizes) in order to test the sensitivity of the results to cell size. The method for setting up the destination should be reported.

4.4. Verification testing report discussion

This discussion is looking at each individual test performed according to the instructions and with results presented according to the Reporting Template in Annex A. The filled reporting templates are presented in Annex B. The discussion includes which features worked in the model, which features could not be represented in the model, discrepancies in the results and suggestions to what could have caused the discrepancies.

The test conducted within the scope of this thesis relate to the traffic component of WUI-NITY. Therefore, the test concerning pedestrian modelling have not been conducted and are omitted here.

A short summary of the key findings that can be obtained from the tests performed for the traffic component is presented here.

Test T.1a. Uni-directional single vehicle flow. This feature can be explicitly represented in the model. One of the configurations had a difference in results between simulation and hand-calculation. The difference for the 90 km/h configuration was 2 %. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test T.1b. Uni-directional single vehicle flow. This feature can be explicitly represented in the model. There was a difference in results between simulation and hand-calculation of 0.9 %. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test T.2. Background traffic. This feature can be implicitly represented in the model. There was a difference in results between simulation and hand-calculation of 1 %. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test T.3. Change in carriageway configuration. This feature can be explicitly represented in the model. One of the configurations had a difference in results between simulation and hand-calculation. The difference for the density level 5 configuration was 6 %. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations. In particular, the stall speed was approximated to 1.08 km/h in WUI-NITY rather than 1 km/h adopted in the hand calculations. The long runtime at this density level makes this small difference in assumed speed more visible.

Test T.4. Relationship between speed-density and flow-density. This feature can be explicitly represented in the model. Comparing the plotted relationship between driving speeds and vehicle densities as well as vehicle flow and vehicle density with underlying assumptions shows that the relationship used do not exceed the values of the underlying assumptions.

Test T.5. Vehicle speed reduction in reduced visibility conditions. This feature can be explicitly represented in the model. Three of the configurations had no difference in results between simulation and hand-calculation. The difference for the other configurations ranged between 0.5 % and 8 %. The difference in results increase for configurations with higher visibility level and density level, with density level having higher impact. Density level 5 has lower difference in result compared to density level 4. In particular, the stall speed was approximated to 1.08 km/h in WUI-NITY rather than 1 km/h adopted in the hand calculations. The long runtime at this density level makes this small difference in assumed speed more visible (this is capped with a time limitation that prevents the result from exceeding 3600 s). The overall difference in results is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g., due to approximation of the curve during its programming) and hand calculations.

Test T.6. Flow at destination. This feature can be explicitly represented in the model. The maximum flow threshold was not exceeded during the entire period of the test by the simulator.

Test T.7. Group evacuation. This feature cannot be represented in the model since it is a microscopic model.

Test T.8. Lane changing/overtaking. This feature cannot be represented in the model since it is a microscopic model.

Test T.9. Acceleration/deceleration. This feature cannot be represented in the model since it is a microscopic model.

Test T.10. Road accident. This feature can be implicitly represented in the model. One of the configurations had a difference in results between simulation and hand-calculation. The difference for the configuration with stall speed of 1 km/h in results between simulation and hand-calculation of 0.007 %. The difference in result is small enough to be considered negligible. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test T.11. Intersection. This feature can be partially represented in the model, i.e. this is a macroscopic model so only vehicles at aggregated levels are considered at intersections. There was no difference in results between simulation and hand-calculation.

Test T.12. Forced Destination. This feature can be explicitly represented in the model. There was no difference in results between simulation and expectations.

Test T.13. Destination choice in traffic. This feature can be explicitly represented in the model. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test T.14. Route choice in traffic. This feature can be explicitly represented in the model. Both configurations had a difference in results between simulation and hand-calculation. The difference for the long route configuration was 0.8 %. The difference for the short route configuration was 0.8 %. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test T.15. Vehicle demand vs arrival distribution. This feature can be implicitly represented in the model. There was no difference in result between simulation, and hand-calculation and expectations in either of the configurations.

Test WT.1. Route loss. This feature was not tested.

Test WT.2. Lane reversal. This feature can be explicitly represented in the model. One of the configurations had a difference in results between simulation and hand-calculation. The difference for the density level 4 configuration was 1 %. This is caused by the slightly different speed-density relationship equation implemented in the simulator (e.g. due to approximation of the curve during its programming) and hand calculations.

Test WT.3. Loss of exit or shelter. This feature can be explicitly represented in the model. There was no difference in result between simulation and expectations.

Test WT.4. Refuge capacity. This feature can be implicitly represented in the model. There was no difference in result between simulation and expectations.

Most of the verification test could be conducted in the simulation except a set of tests that required a microscopic modelling approach. The difference in result ranged from 0,5 – 8 %. Approximations in the implementation of the fundamental diagram causes slight difference in speeds used in the simulation are affecting test results. The tests that had no difference in result also had differences in used speeds, the reasons these did not influence the results could be caused by time-step approximations errors that made the difference negligible. The tests had a short run time, having less time steps to cause this discrepancy. In the tests with lower result differences, the test run time was overall shorter because of higher used speeds, providing less time-steps to give time differences. In the test with higher result differences, the test run time was overall long and was approaching or using stall speed. When the stall speed is used, the test run time increases close to 3600 time steps. The difference in speeds used in simulation and hand calculation are very low (≈ 0.07 km/h), but in a test with 3600 time steps, the impact of the speed difference becomes more prominent the longer the test goes on. All in all, WUI-NITY seemed to have performed as expected and differences with hand calculations could overall be considered negligible considering the uncertainty associated with the scale of a real event.

5. Validation testing for WUI fire traffic evacuation models

Validation is part of the verification and validation process to ensure that a simulation model produces not only accurate results, but realistic results that can be compared to real-life case studies or experimental data. The validation process is important to grant the model credibility since the results of the model can change the decisions-making of people affected or required to make decision based on the model results. In this case, the functionality subjected to validation is a core traffic component in WUI-NITY, i.e., the fundamental diagrams (i.e., speed-density and flow-density relationships). The fundamental diagrams are only a part of many aspects that needs to be validated in the future, such as route choice, response behaviour, etc.

5.1. Preliminary validation of speed-density and flow-density relationships

A simple preliminary validation of one of the core traffic components needed for evacuation is performed, i.e., the so called fundamental diagrams (Dixit & Wolshon, 2014) (i.e., speed-density and flow-density relationship) adopted in WUI-NITY. This is performed by extracting traffic data from the PeMS database for the traffic quantities density, flow and speed before and during the Kincade Fire evacuation 2019 on Highway 101. The data is used to construct new fundamental diagrams for speed-density and flow-density during evacuation traffic and routine non-emergency traffic, which is then compared the theoretical fundamental diagram used in WUI-NITY to see if WUI-NITY accurately represents a real WUI traffic evacuation. This first validation testing of evaluating fundamental diagrams is deemed an appropriate initial test to ensure that a core the fundamental element of the model work realistically.

The theoretical fundamental diagram used in WUI-NITY is based on values provided by the Highway Capacity Manual (TRB, 2016) and it is an implementation of the LWR model. This means that there is an individual curve for each road type implemented (Ding, 2011) (Li, et al., 2012) (Lighthill & Whitham, 1955) (Richards, 1956) (Wahlqvist, et al., 2021). In this case where Highway 101 has a freeway road type with a speed limit of ≈ 113 km/h (70 mph) and is compared to the theoretical fundamental diagram, the comparison is only made to one individual curve in WUI-NITY based on the road type. This is a first attempt of validation based on a commonly adopted type of road. The same validation procedure needs to be done for different road types (e.g., living street, residential, trunk).

The theoretical fundamental diagram used in WUI-NITY is based on Lighthill-Whitham-Richard model (Ding, 2011) (Li, et al., 2012) (Lighthill & Whitham, 1955) (Richards, 1956) and on the *Highway Capacity Manual (*HCM) (TRB, 2016) in which a freeway with free-flow speed of ≈ 113 km/h (70 mph) has a capacity of 1900 vehicles/lane. This is the diagram for the road type under consideration. WUI-NITY modifies the diagram for the different road types depending on the speed and capacity values mentioned in the HCM. This data is used to calculate the maximum density the freeway can have before the traffic stops due to congestion. By assuming the graph to be parabolical, the maximum capacity is reached at half the free-flow speed at ≈ 56.5 km/h (35 mph) (TRB, 2016), see Figure 3. The maximum flow is assumed to be reached at half of the maximum density which is 1900/56.5=33.73 vehicles/km/lane, see Figure 4.

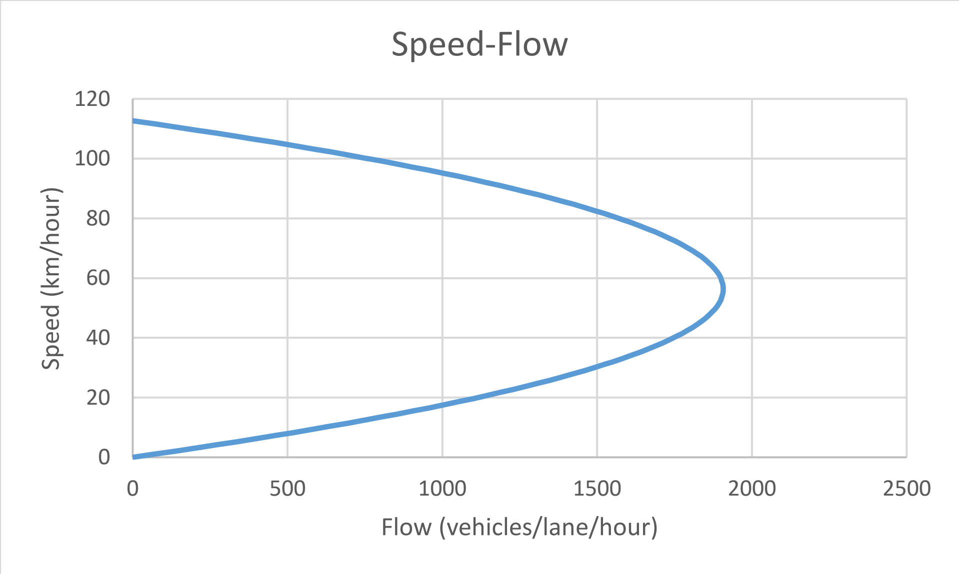


Figure 3 - Speed-flow plot used in theoretical fundamental diagram adopted in WUI-NITY for the road type under consideration.

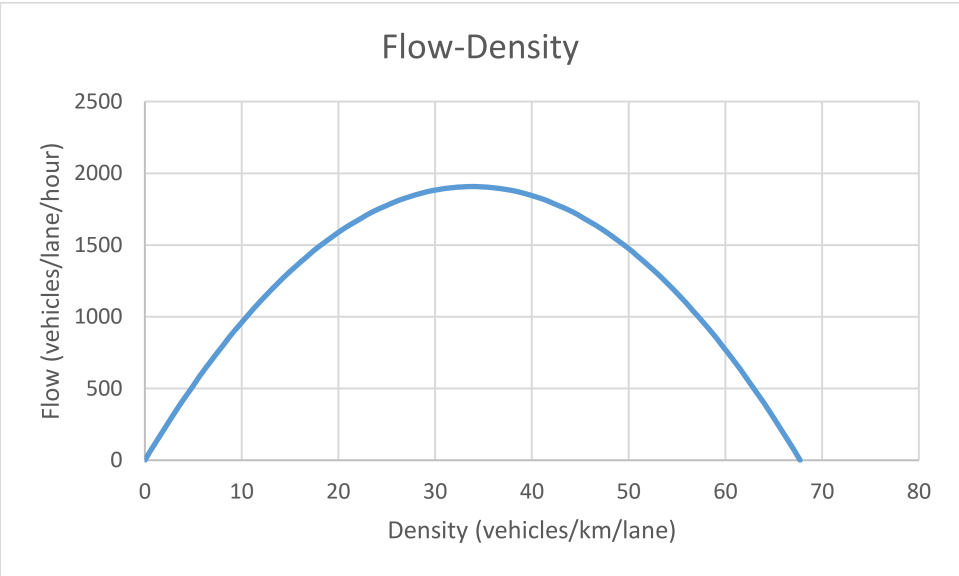


Figure 4 - Flow-density plot used in theoretical fundamental diagram adopted in WUI-NITY for the road under consideration.

The maximum density is then 33.73*2= 67.46 ≈ 67 vehicles/km/lane (≈109 vehicles/mile/lane). In the current case study, the theoretical fundamental diagram is constructed using the free-flow speed 113 km/h, the capacity 1900 vehicles/lane and the density 67 vehicles/km/lane.

5.2. Data sourcing and extraction

The analyzed traffic data was collected by the California Department of Transportation (Caltrans). The data is accessed through the Caltrans Performance Measurement System (PeMS) website[2] which gather real time traffic data (e.g., speed, flow, occupancy) from sensors distributed along most of the freeways in California, and creates plots, tables, and exportable files over the collected information (Chao, 2003). The database was chosen to be used because

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

the availability of both routine and evacuation data in open access for a road type commonly present in WUI fire evacuation. The plots were automatically created in PeMS with data for occupancy, speed, and flow over time, see Figure 6 for example. The plots can display two traffic quantities at the time on the vertical axes, as well as the date and time when the data was measured on the horizontal axis. The description text above the plot describes what traffic quantity is displayed on the primal axis, how many measurements are taken during the time interval, the detector name and freeway, and the range of the time interval. In the flow-density plot, the flow is measured in vehicles/hour for all lanes total, and not vehicles/lane/hour. The traffic detection systems used by the PeMS are mostly automatic loop detectors but can accept traffic data as long as it is collected electronically and automatically. Other measurement systems can be used, such as magnetometers, which operates in similar ways to the loop detector with pulse measurements. (Chao, 2003), (Klein, 1996). The loop detectors use a wire coil that measures change in inductance when a vehicle drives by, see Figure 5. The time it takes for the inductance to pass both thresholds represent a pulse and the time it took a vehicle to pass the loop. From this can speed, flow and occupancy be measured.

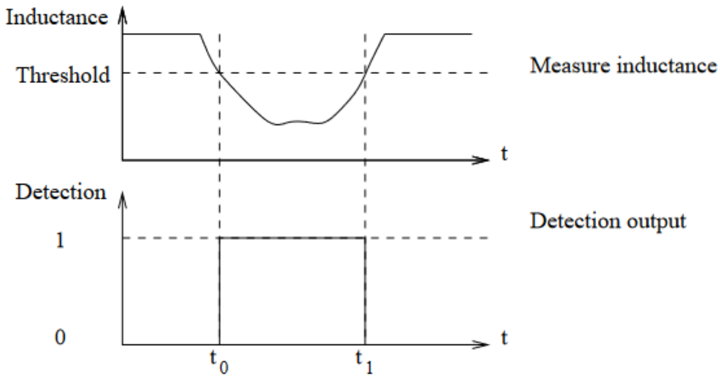


Figure 5 – Loop detection system using change in inductance on the wire loop. Picture taken from (Chao, 2003).

Most of the loops are single loops, but there are also double loops that are better at measuring speed. They are placed under the road surface and located on all lanes, on- and off-ramps on thousands of highway locations in California. (Chao, 2003) The data is used to build a scatter plot in which regression models are obtained to allow for comparison with the theoretical fundamental diagram, (both considering speed-density and flow-density relationships).

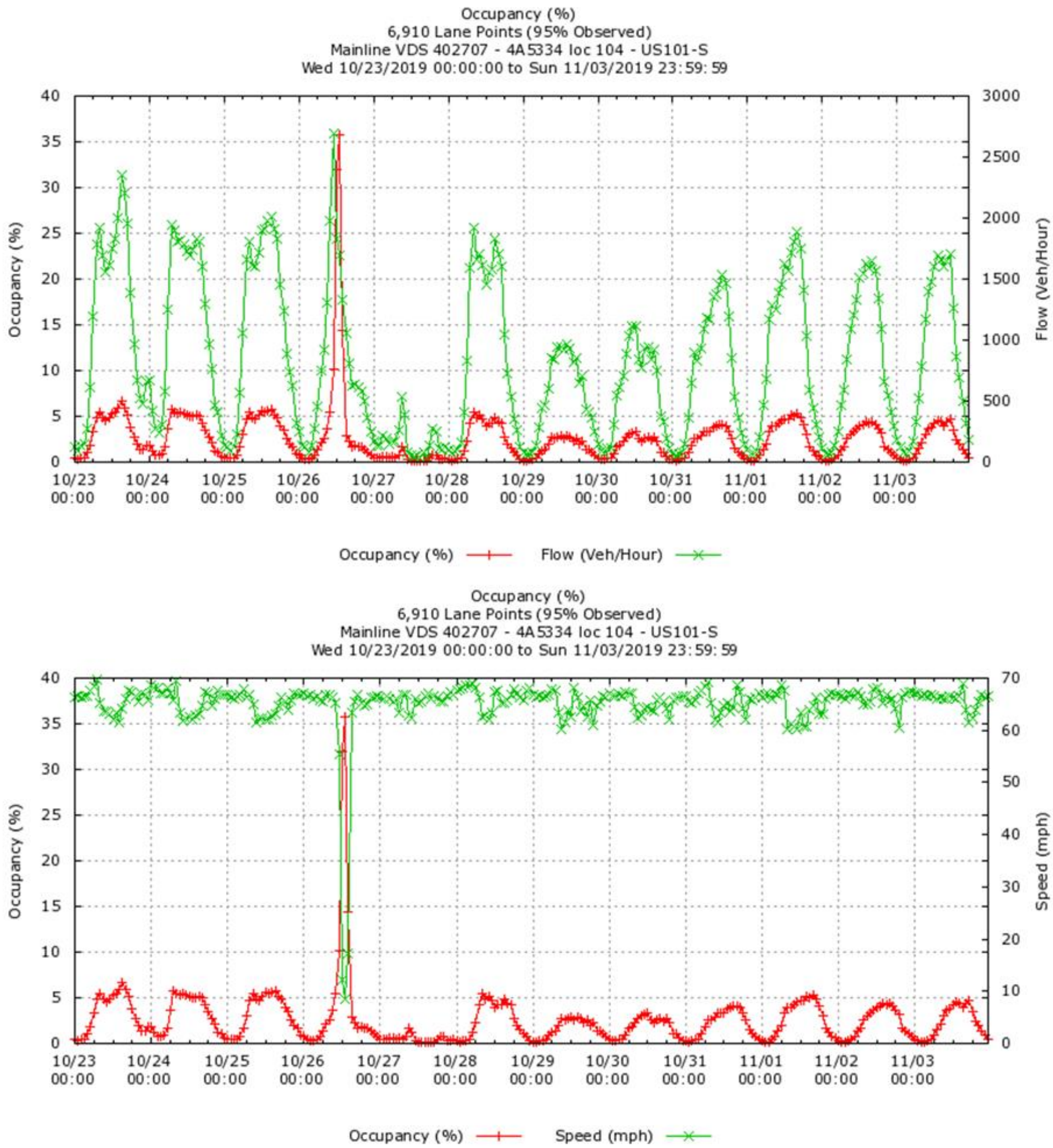


Figure 6 - Example plot extracted from PeMS presenting occupancy, speed, and flow

The PeMS does not provide data on density in the unit vehicles/km/lane which is needed to create the fundamental diagram, but on occupancy instead, i.e., how many percent of the road is covered by vehicles. The occupancy can be converted into density by using Equation 1 (Chao, 2003).

$$Density = \frac{Occupancy}{Average\ vehicle\ length\ (m)} \times 1000\ m\ per\ km \quad \text{[Equation 1]}$$

The average vehicle length is assumed approximately 4.5 m long (Sellén, 2021).

The PeMS does not provide data on speed in the unit of km/h which is needed to create the fundamental diagram, but on mph instead. The mph can be converted into km/h by using Equation 2 (Thompson & Taylor, 2008).

$$Speed\ \left(\frac{km}{h}\right) = \frac{5280 \times \frac{1200}{3937}}{1000} \times Speed\ (mph) \quad \text{[Equation 2]}$$

When knowing which detector and time interval to look at, the data can be extracted as an .xls file to get manageable data. The extraction was done twice for each location since only two traffic quantities can be selected at the same time. First occupancy and flow were extracted, then occupancy and speed. The granularity of the gathered data was selected to be 5 minutes interval to get the most accurate data available in the database. In addition, 1 hour interval data was also extracted for ensuring consistency. Selecting the granularity to 5 minutes provides data on flow/5 minutes instead of the desired unit of flow/hour. To get the desired unit, the flow/5 minutes were multiplied by 12. This is not the actual flow that was observed, but a normalization to get a compatible unit with the other quantities. The lanes from which to gather data from could also be selected, either individual lanes, all of the lanes or aggregated lanes. The aggregated data uses an average from all lanes to calculate occupancy and speed per lane but uses the total flow from all lanes, which needs to manually be divided by the number of lanes observed at that sensor to get the desired flow per lane. See Figure 7 for an example over the input data panel in PeMS and see Table 3 and Table 4 for examples of extracted data from the PeMS database.

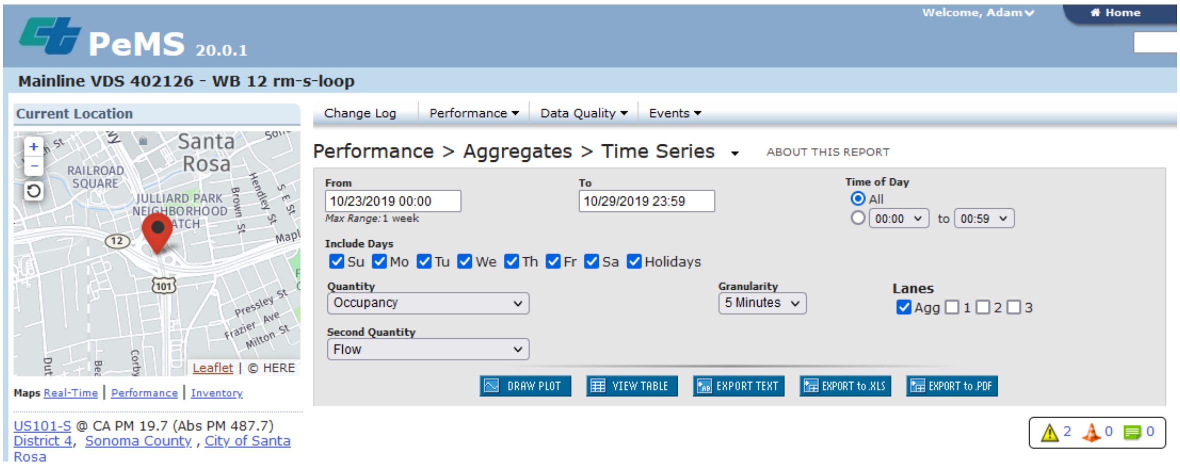


Figure 7 - Input data panel from the PeMS database.

							Data Quality	
5 Minutes	Lane 1 Occ (%)	Lane 1 Flow (Veh/5 Minutes)	Lane 2 Occ (%)	Lane 2 Flow (Veh/5 Minutes)	Occupancy (%)	Flow (Veh/5 Minutes)	# Lane Points	% Observed
10/23/2019 00:00	0.2	3.0	1.0	12.0	0.6	15.0	2	100.0
10/23/2019 00:05	0.0	1.0	1.0	11.0	0.5	12.0	2	100.0
10/23/2019 00:10	0.5	7.0	0.6	7.0	0.5	14.0	2	100.0
10/23/2019 00:15	0.2	3.0	0.5	8.0	0.4	11.0	2	100.0
10/23/2019 00:20	0.2	3.0	0.6	8.0	0.4	11.0	2	100.0
10/23/2019 00:25	0.1	2.0	0.4	6.0	0.2	8.0	2	100.0
10/23/2019 00:30	0.1	2.0	0.8	10.0	0.5	12.0	2	100.0

Table 3 - Example of extracted data from PeMS database for occupancy and flow for individual lanes and aggregated lanes.

							Data Quality	
5 Minutes	Lane 1 Occ (%)	Lane 1 Speed (mph)	Lane 2 Occ (%)	Lane 2 Speed (mph)	Occupancy (%)	Speed (mph)	# Lane Points	% Observed
10/23/2019 00:00	0.2	71.2	1.0	65.1	0.6	66.3	2	100.0
10/23/2019 00:05	0.0	71.5	1.0	64.5	0.5	65.1	2	100.0
10/23/2019 00:10	0.5	71.2	0.6	64.5	0.5	67.8	2	100.0
10/23/2019 00:15	0.2	71.1	0.5	64.9	0.4	66.6	2	100.0
10/23/2019 00:20	0.2	71.2	0.6	64.9	0.4	66.6	2	100.0
10/23/2019 00:25	0.1	71.2	0.4	65.3	0.2	66.8	2	100.0
10/23/2019 00:30	0.1	71.0	0.8	65.0	0.5	66.0	2	100.0

Table 4 - Example of extracted data from the PeMS database for occupancy and speed for individual lanes and aggregated lanes.

5.3. Kincade Fire case study

Data concerning evacuation traffic and routine non-emergency traffic from the Kincade Fire evacuation 2019 was analyzed as a case study in this validation. The Kincade Fire data set was selected because it is a well-documented case and has been subjected to other studies allowing for future comparison (Zhao, et al., 2021) (Zhao, et al., 2021) (Wong, et al., 2020). To know when and where to look for useful traffic data to extract from the PeMS database, the *2019 Kincade Fire After Action Report* was used since it contains information about the fire development and the evacuation (Sonoma Operational Area and the County of Sonoma, 2020).

The Kincade Fire started on October 23, 2019, northeast of Geyserville in Sonoma County, California and was contained on November 6, 2019. The fire burned 77,758 acres of land, and over 186,000 residents had to evacuate. The Sonoma County is divided into zones to easier manage evacuations during emergencies. The California Department of Forestry and Fire Protection (CAL FIRE) is responsible for the emergency evacuation planning (California Department of Forestry and Fire Protection, 2019) and issued the evacuation orders during the Kincade fire, see Table 5. The zones were also divided into sub-zones A, B, C etc. The zones are geographically shown in Figure 8 with all the highways going through the area.

CAL FIRE Evacuation Orders		
Date	Zones	Population
October 23	Geyserville	874
October 26 AM	1,2,3	44,131
October 26 PM	1,2,3,4,5,7	83,764
October 27	1,2,3,4,5,6,7,8,10	186,651
October 28	1,2,3,4,5,6,8A,9,10	136,148
October 29	1,2,3,4B,5,6,8A,9,10	133,740
October 30	1B,2,3C,5B	3,381
October 31	1B,2,3C,5B	3,381
November 1	1C,2,3C,5B (zone-size changes)	2,608
November 2	1C,2,3C,5B (zone-size changes)	978
November 3	NA	0

Table 5 - Evacuation orders active during which date, what zones and how large population were affected (Sonoma Operational Area and the County of Sonoma, 2020).

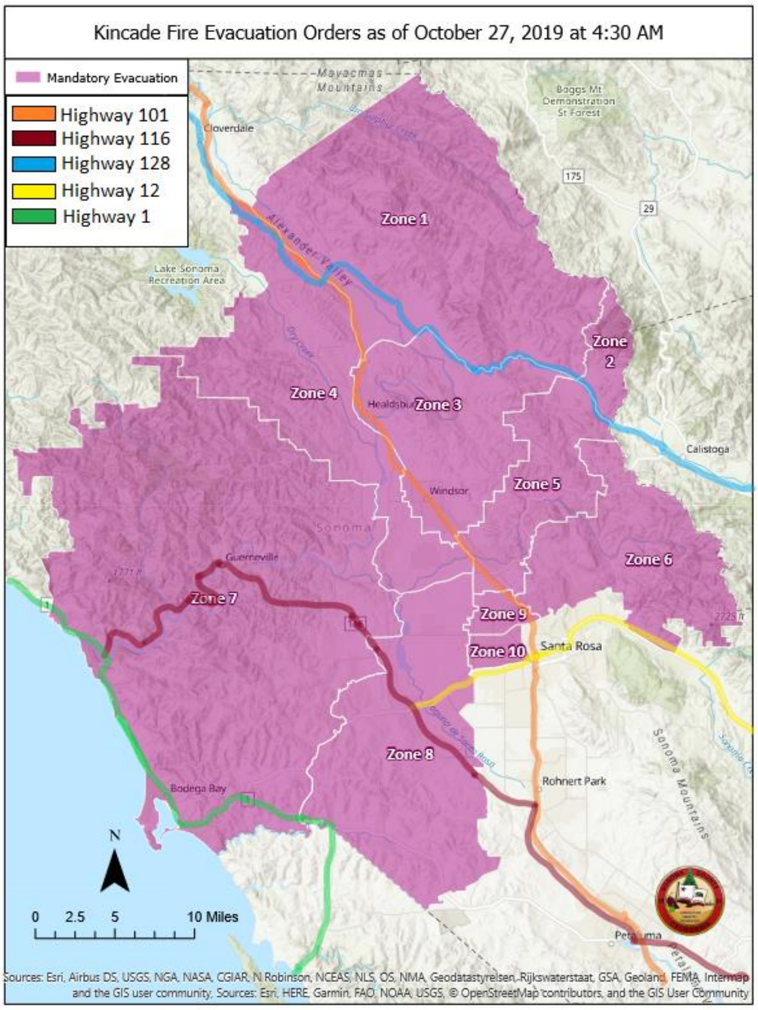


Figure 8 - The 10 mandatory evacuation zones with connecting highways highlighted. Picture taken from (Sonoma Operational Area and the County of Sonoma, 2020).

The highways that are passing through the mandatory evacuation zones are Highway 101, 116, 128, 12, and 1, with Highway 101 being the largest and most important highway for Sonoma County (Sonoma County Transportation Authority, 2021). When checking the PeMS database for these five highways, only highways 101, 12 and 1 have been found to have traffic detection system on them. Highway 12 however does not have a traffic detection system in the area around the evacuation zones. Highway 1 on the other hand is far away from where the majority of the population is located, making it less available as an option for a quick evacuation in an emergency and being mostly accessible to the population of Zone 7. Highway 101 is a major highway of Sonoma County and it goes straight through the evacuation zones making it accessible for a majority of people in Zones 1-10. Highway 101 also has an extensive number of traffic detection system on it, making it the best highway to gather traffic evacuation data for the scope of this study. Highway 101 has ≈113 km/h (70 mph) as a speed limit in most places, sometimes ≈ 105 km/h (65 mph) with mostly 2 lanes in rural setting and 3-4 lanes in urban setting. Table 6 shows the width of road elements at one location for Highway 101 at the intersection with Highway 12.

Roadway Information (from TSN)	
Road Width	24 ft
Lane Width	12.0 ft
Inner Shoulder Width	5 ft
Inner Shoulder Treated Width	5 ft
Outer Shoulder Width	8 ft
Outer Shoulder Treated Width	8 ft
Design Speed Limit	70 mph
Functional Class	Principal Arterial W/ C/L Prin Arterial
Inner Median Type	Unpaved
Inner Median Width	46 ft
Terrain	Flat
Population	Urbanized
Barrier	Three Beam Barrier
Surface	Concrete
Roadway Use	

Table 6 - Roadway Information (from TSN) at the Highway 101 and Highway 12 intersection. Table taken from the PeMS database.

The process of deciding when and where to gather traffic data was done in two steps. The first step was to take multiple samples along the 80 km long distance between Cloverdale and Petaluma to check for potential useful locations during the timespan when the Kincade Fire started to when the mandatory evacuation orders were lifted, from October 23 to November 3. October 23 is also the date which the first mandatory evacuation order was issued, see Table 7.

Date	Event
23/10	Fire ignition and first mandatory evacuation order is given
27/10	187 000 people are under mandatory evacuation order
3/11	No mandatory evacuation order active
6/11	Fire is fully contained

Table 7 - Brief timeline of major events during Kincade Fire 2019

The samples were taken both north- and southbound directions on US101, and the granularity of the time interval was 1 hour. The locations to gather traffic data from depends on the placement of the sensor, i.e., desired locations may not be available to gather data at. However, the frequency of sensor placement is high, on average one sensor every 840 m providing many options for suitable sensor placements. The location for the sensors was decided to be between the major cities along US101, as well as north of Cloverdale and south of Petaluma, see Figure 9. Based on the time interval and locations for the sensors, 32 plots were automatically created in PeMS with data for occupancy, speed, and flow over time, Annex C. The plots can only have two out of three desired traffic quantities at the time, making the 32 plots more accurate 16 pairs of plots, since the location and time interval are the same.

CITY	DATA POINT
	4A5334 loc 147 (2 lanes) (it has 3 lanes on Google Street maps)
CLOVERDALE	
	4A5334 loc 130 (2 lanes)
GEYSERVILLE	
	4A5334 loc 116 (2 lanes)
HEALDSBURG	
	4A5334 loc 104 (2 lanes)
WINDSOR	
	Hopper Ave rm-s-loop (3 lanes)
SANTA ROSA	
	4A5334 loc 78 (3 lanes)
ROHNERT PARK	
	4A5334 loc 66 (2 lanes)
PETALUMA	
	4A5334 loc 54 (2 lanes)

Table 8 -Name of the data point in PeMS, with number of lanes at the location and it's relative position to the cities along US101.

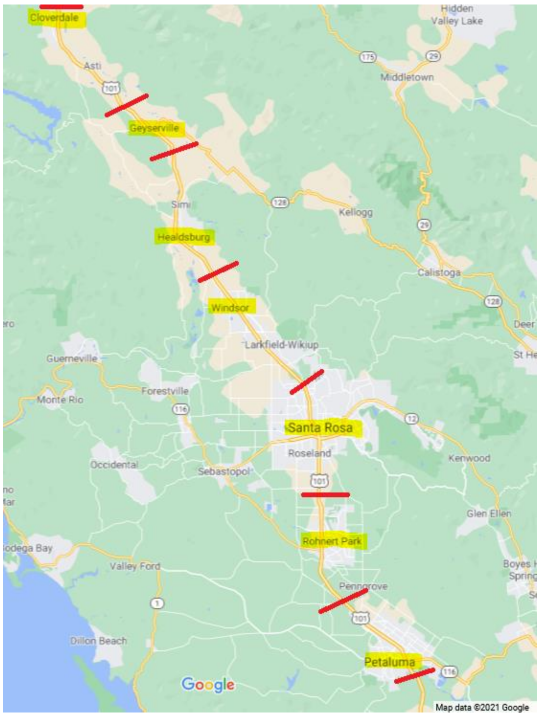


Figure 9 -Map over U101 with highlighted cities and location of data points in red.

The second step was to filter out the useful locations and timestamps from the useless. Useful data contains clear data where the traffic density increases to a point in which the flow and speed decreases. In contrast, data that do not consider how the increase in density negatively impact speed and flow are less useful, i.e., the road capacity can handle the current traffic volume without difficulties and free flow conditions are observed. A total of 16 pair of plots were extracted where the peaks with roughly more than 20 % occupancy were selected to be used to construct the fundamental diagrams used for validation. The peaks with more than 20 % occupancy have an observable impact on speed and flow, and they are needed to build a complete fundamental diagram as possible with a wide range of measured densities. Values on free flow were also added to the fundamental diagram to have a complete picture of the flow-density and speed-density relationships. Many different locations were selected along the highway in order to contain different density ranges and build comprehensive fundamental diagrams, see Table 9 which also includes incident reported close to the selected location. The locations and timestamps were selected from a larger time interval at each location, see Annex C.

Detector name	Timestamp	Incident
US101-S 4A5334 loc 104	26/10 00:00 - 26/10 23:59	
US101-S Hopper Ave rm-s-loop	23/10 00:00 - 23/10 23:59, 25/10 00:00 - 25/10 23:59	1 traffic hazard at the Hopper Ave Onramp for 39 min at 25/10 23:09
US101-N 4A5334 loc 78	23/10 00:00 - 23/10 23:59	
US101-S 4A5334 loc 78	27/10 00:00 - 27/10 23:59	

US101-S 4A5334 loc 66	24/10 00:00 - 24/10 23:59, 26/10 00:00 - 26/10 23:59	
US101-S SB College Ave rm-s-diag	27/10 00:00 – 27/10 23:59	1 traffic hazard at the College Ave Offramp for 23 mins at 27/10 00:33
US101-S oppo Third St rm-s-diag	27/10 00:00 – 27/10 23:59	
US101-S WB 12 rm-s-loop	27/10 00:00 – 27/10 23:59	1 traffic collision-unknown injury at the Us101 S Sr12 W Con / Sr12 W for 0 mins at 27/10 05:12
US101-S EB 12 rm-s-diag	27/10 00:00 – 27/10 23:59	1 traffic collision-no injury at the Us101 S Sr 12 Con/ Us101 S Sr 12 E Con for 6 mins at 27/10 04:52
US101-S Baker Ave rm-s-diag	27/10 00:00 – 27/10 23:59	
US101-S Hearn Ave rm-s-diag	27/10 00:00 – 27/10 23:59	1 traffic hazard at the Hearn Ave Onramp for 2 mins at 27/10 08:26
US101-S 4A5334 loc 80	23/10 00:00 – 29/10 23:59	
US101-S Todd Rd rm-s-diag	23/10 00:00 – 29/10 23:59	1 Report of fire at the Todd Rd Offramp for 2 mins at the 28/10 17:33
US101-S Rohnert Park Expwy rm-s-loop	23/10 00:00 – 29/10 23:59	1 traffic collision-unknown injury at the Rohnert Park Offramp for 30 mins at the 23/10 11:29 1 traffic collision-unknown injury at the Rohnert Park E Onramp for 50 mins at the 26/10 11:11
US101-S 4A5334 loc (76) / 76A	23/10 00:00 – 29/10 23:59	

Table 9 - Detector name, timestamp and incidents at the locations used in fundamental diagram for evacuation traffic.

With all the evacuation data extracted and occupancy converted to density, speed converted from mph to km/h and flow normalized, the fundamental diagram for evacuation traffic was created, see Figure 10 and Figure 11. The evacuation traffic needs to be compared to what traffic usually looks like during non-emergency to investigate how the emergency conditions affect driving behavior. The routine traffic was also retrieved to build corresponding fundamental diagram using the same method for the evacuation traffic, except the time interval used to look for useful high-density peaks was one week before the Kincade Fire started, from 16/10 to 22/10. Based on the plots in Annex C, the locations and timestamps to be used in the fundamental diagram were chosen. The location for the sensor were on the same location as the evacuation traffic, but with different timestamps, see Table 10, which also includes incident reported close to the selected location. The routine traffic data were extracted from PeMS the same way as evacuation traffic data and converted and normalized the same way for speed, density, and flow. The converted and normalized data was crossed checked with the hourly resolution data to ensure the conversion and normalization was performed correctly. With this data the fundamental diagram for routine traffic was created, see Figure 10 and Figure 11.

Detector name	Timestamp	Incident
US101-S 4A5334 loc 104	16/10 00:00 - 16/10 23:59	
US101-S Hopper Ave rm-s-loop	16/10 00:00 - 17/10 23:59, 21/10 00:00 - 22/10 23:59	1 traffic collision-no injury at the Mendocino Ave Offramp for 19 mins at 22/10 16:36
US101-N 4A5334 loc 78	16/10 00:00 - 17/10 23:59	
US101-S 4A5334 loc 78	21/10 00:00 - 21/10 23:59	
US101-S 4A5334 loc 66	16/10 00:00 - 16/10 23:59, 20/10 00:00 - 20/10 23:59	
US101-S SB College Ave rm-s-diag	17/10 00:00 - 17/10 23:59	
US101-S oppo Third St rm-s-diag	17/10 00:00 - 17/10 23:59	
US101-S WB 12 rm-s-loop	17/10 00:00 - 17/10 23:59	
US101-S EB 12 rm-s-diag	17/10 00:00 - 17/10 23:59	
US101-S Baker Ave rm-s-diag	17/10 00:00 - 17/10 23:59	1 traffic collision-unknown injury at the Baker Ave onramp for 7 mins at 17/10 12:28
US101-S Hearn Ave rm-s-diag	17/10 00:00 - 17/10 23:59	
US101-S 4A5334 loc 80	16/10 00:00 – 22/10 23:59	
US101-S Todd Rd rm-s-diag	16/10 00:00 – 22/10 23:59	1 traffic hazard at Todd Rd Onramp for 44 mins at 16/10 14:36 1 Traffic hazard at Todd Rd Offramp for 1 min at 17/10 05:38 1 DOT-Request CalTrans Notify at Todd Rd Offramp for 12 mins at 18/10 15:33 1 Wrong Way Driver at Todd Rd Onramp for 2 mins at 19/10 12:50 1 DOT-Request CalTrans Notify at Todd Rd Offramp for 42 mons at 19/10 14:22
US101-S Rohnert Park Expwy rm-s-loop	16/10 00:00 – 22/10 23:59	

US101-S 4A5334 loc (76) / 76A	16/10 00:00 – 22/10 23:59	1 traffic collision-unknown injury at Gravenstein Hwy Offramp for 49 min at 18/10 12:18

Table 10 - Detector name, timestamp and incidents at the location used in fundamental diagram for routine traffic.

5.4. Comparison of actual data and theoretical curve in WUI-NITY for the case study

Figure 10 shows the Flow-Density relationship for the theoretical fundamental diagram used in WUI-NITY and the extracted traffic data from PeMS. The extracted data is added as a scatter plot with a regression model applied to the scattered data. In the Flow-Density plot, the regression models are the same type of equation as the theoretical fundamental diagram, for evacuation traffic the regression model is a polynomial equation of order 2 with $R^2 = 0.7209$, see Equation 3. For the routine traffic the regression model is a polynomial equation of order 2 with $R^2 = 0.8236$, see Equation 4.

$$Q = -0.5812\, d^2 + 62.291d \qquad \text{[Equation 3]}$$

$$Q = -0.7072\, d^2 + 68.653d \qquad \text{[Equation 4]}$$

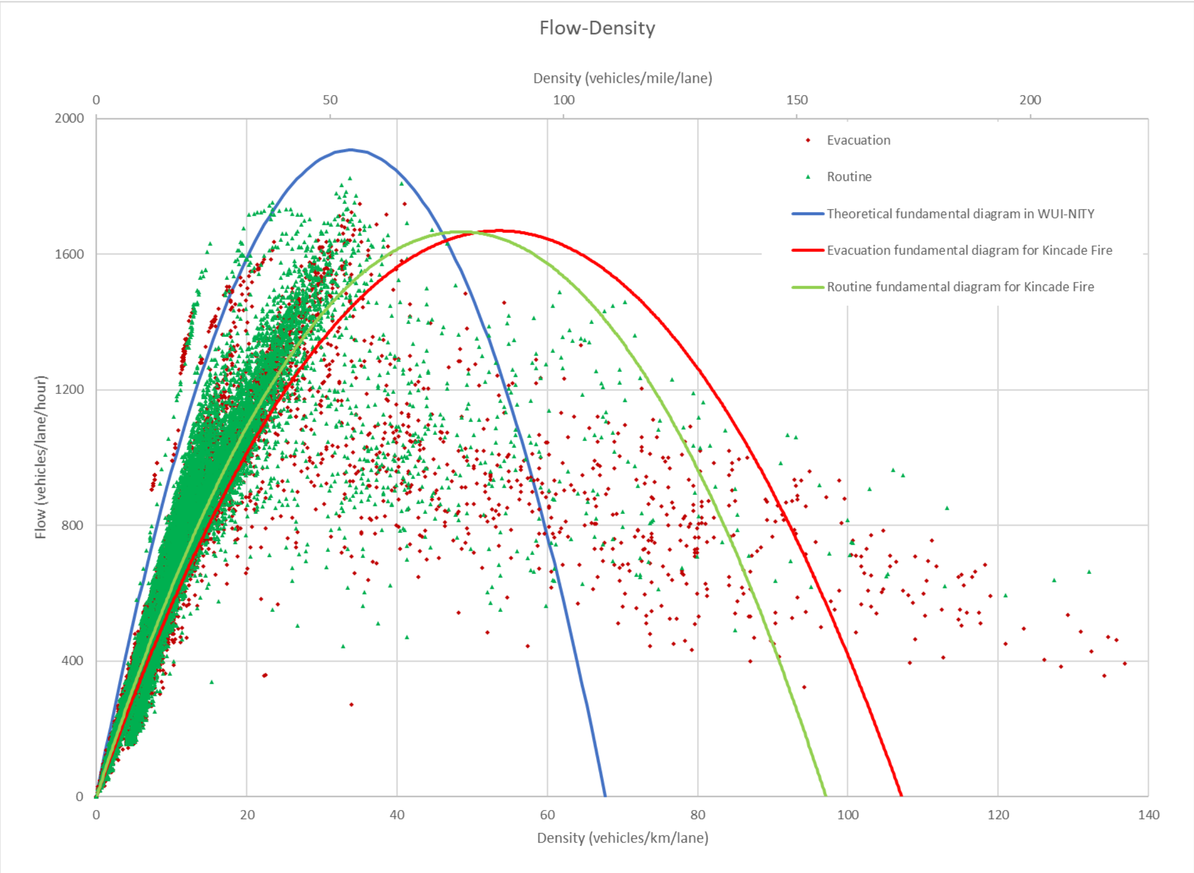


Figure 10 - Flow-Density relationship for theoretical, evacuation and routine traffic with polynomial regression model.

In the Flow-Density plot, see Figure 10, the theoretical flow assuming a parabolical trend increases to a maximum value of 1900 vehicles/lane/hour at around density 35 vehicles/km/lane, and then decrease until it reaches around density 70 vehicles/km/lane. The regression model for both the evacuation and routine traffic flow reaches around 1700 vehicles/hour, but at different densities. The routine traffic reaches maximum flow at around 50 vehicles/km/lane and evacuation traffic reaches maximum flow at around 55 vehicles/km/lane. The routine traffic flow decreases to 0 at around 100 vehicles/km/lane and the evacuation traffic flow decreases to 0 at around 110 vehicles/km/lane. Both routine and evacuation traffic regression models reach a higher maximum density of around 30-40 vehicles/km/lane and have a lower maximum flow of around 200 vehicles/hour compared to the theoretical curve. The maximum flow for evacuation and routine traffic is reached at higher densities than the theoretical curve. The theoretical curve encloses most of the lower density measurements but does not represent the higher density measurements. Both evacuation and routine traffic regression models only represent the lower edge of the flow in the lower density measurements. The regression models represent too high flow in the middle density measurements and then the flow drops too early to accurately represent the higher density measurements. Only a few measurements come close to reaching the theoretical maximum flow, but none actually does it in the gathered measurements (neither for routine nor evacuation conditions).

At the higher densities, the measured evacuation flow does seemingly decrease until it reaches a certain point at density 140 vehicles/km/lane and flow 400 vehicles/lane/hour. The difference between the maximum and minimum flow where measured data can be found seem to decrease from its maximum difference of around 1000 vehicles/lane/hour at around 30 vehicles/km/lane until the density reaches 140 vehicles/km/lane. The minimum evacuation flow seems to only decrease slightly between 30 and 140 vehicles/km/lane and stays at around 400 vehicles/lane/hour, while the maximum evacuation flow seems to decrease faster between in the same density range from 1700 to 400 vehicles/lane/hour. The same can be described for the measured routine flow at the higher densities. The measured flow does seemingly decrease until it reaches a point at density 130 vehicles/km/lane and flow 600 vehicles/lane/hour. The difference between the maximum and minimum flow where measured data can be found seem to decrease from its maximum difference of around 1200 vehicles/lane/hour at around 30 vehicles/km/lane until the density reaches 130 vehicles/km/lane. The minimum routine flow seems to only decrease slightly between 30 and 130 vehicles/km/lane, while the maximum routine flow seems to decrease faster between the same density range from 1800 to 600 vehicles/lane/hour.

The measured flow for both routine and evacuation seem to never decrease to 0 vehicles/lane/hour despite the increasing density, but rather 594-663 vehicles/lane/hour for routine and 356-537 vehicles/lane/hour for evacuation. This is likely caused by the aggregated nature of the data (e.g. every 5 min).

Figure 11 shows the Speed-Density relationship for the theoretical fundamental diagram used in WUI-NITY and the extracted traffic data from PeMS. The extracted data is added as a scatter plot with a regression model applied to the scattered data. In the Speed-Density plot, the regression models are as the same type of equation as the theoretical fundamental diagram, for evacuation traffic the regression model is a linear equation with $R^2 = 0.8158$, see Equation 5.

For the routine traffic the regression model is a linear equation with $R^2 = 0.7283$, see Equation 6.

$$v = -1.029d + 112.73 \qquad \text{[Equation 5]}$$

$$v = -0.9717d + 113.27 \qquad \text{[Equation 6]}$$

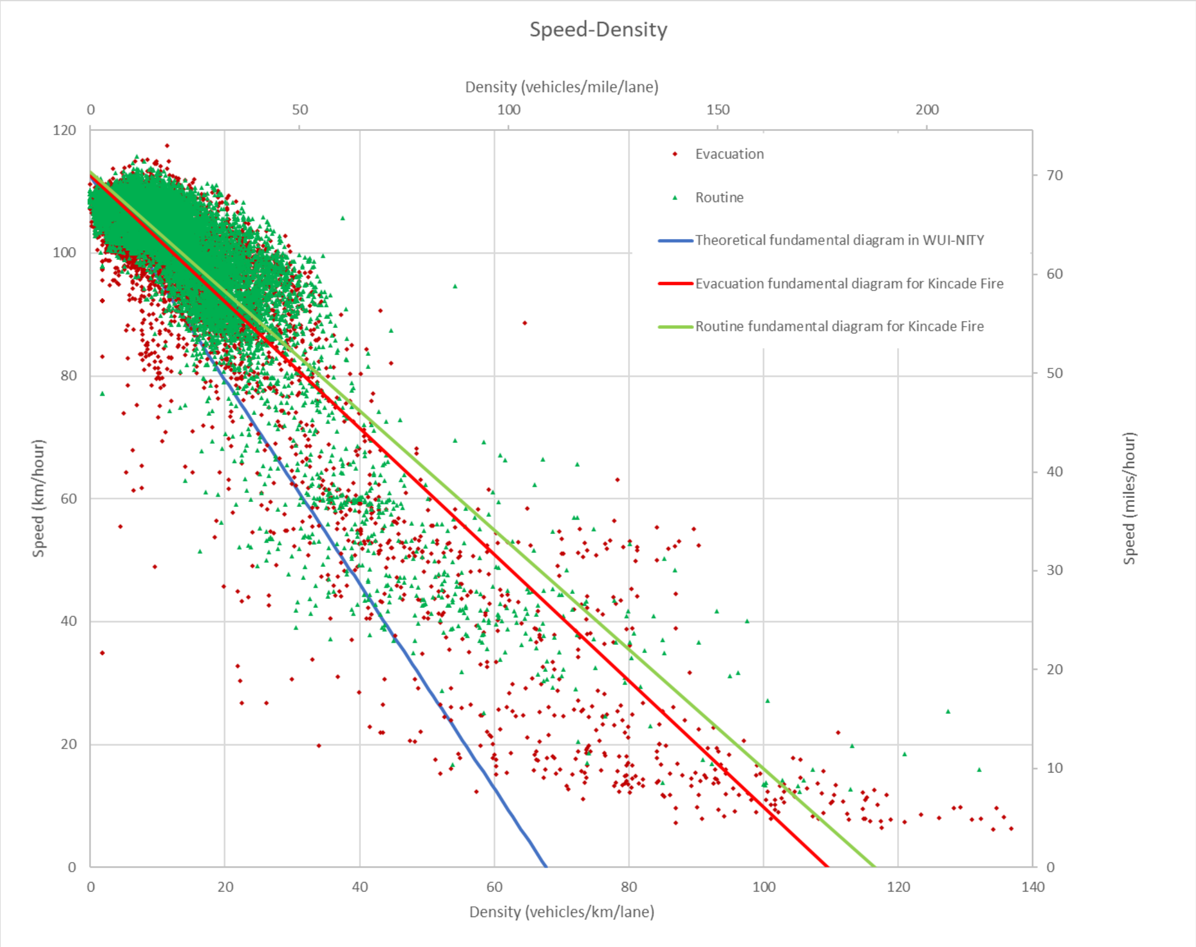


Figure 11 - Speed-Density relationship for theoretical, evacuation and routine traffic with linear regression model.

In the Speed-Density plot, see Figure 11, the theoretical curve has maximum speed of around 110 km/h at 0 vehicles/km/lane and decreases linear to 0 km/h at around density 70 vehicles/km/lane. The regression model for both the evacuation and routine traffic speed has maximum speed of around 110 km/h, but the speed decreases and reach 0 at different densities. The evacuation traffic reaches 0 km/h at around 110 vehicles/km/lane and the routine traffic reaches 0 km/h at around 120 vehicles/km/lane. Both evacuation and routine traffic regression models reach a higher maximum density of around 40-50 vehicles/km/lane compared to the theoretical curve before the speed declines to 0 km/h. The theoretical curve drops in value faster than the evacuation and routine traffic regression models. The regression models represent the speed well at lower density measurements but over-represents the speed in the middle density measurements. The regression models drop in speed too early to accurately represent the speed at high density measurements.

The measured evacuation speed does seemingly decrease linearly until it reaches a certain point at density 120 vehicles/km/lane where the measurements flatten out and the speed becomes almost constant at 10 km/hour with increasing density. The difference between the maximum and minimum speed where measured data can be found varies throughout the densities. In the lower and higher densities 0-5 vehicles/km/lane and 90-140 vehicles/km/lane, the difference in maximum and minimum speed is around 5-10 km/hour while in the middle densities 5-90 vehicles/km/lane the difference in maximum and minimum speed is around 40-60 km/h. The same can be described for the measured routine speed. The routine speed does seemingly decrease linear until it reaches a certain point at 110 vehicles/km/lane where the speed starts to vary at around 20 km/h with increasing density. There are few measurement points in this density range over 110 vehicles/km/lane, making it difficult to make an accurate visual analysis on the speed with increasing density. In the lower and higher densities 0-10 vehicles/km/lane and 100-140 vehicles/km/lane, the difference in maximum and minimum speed is around 5-10 km/hour while in the middle densities 10-100 vehicles/km/lane the difference in maximum and minimum speed is around 30-50 km/hour.

The measured speed for both routine and evacuation seem to never decrease to 0 km/h, despite the increasing density, but rather 12-25 km/h for routine 6-10 km/h and for evacuation. This is likely caused by the aggregated nature of the data (e.g. every 5 min).

Figure 12 shows the Flow-Density relationship for the theoretical fundamental diagram used in WUI-NITY and the extracted traffic data from PeMS. The extracted data is added as a scatter plot with a regression model applied to the scattered data. In the Flow-Density plot with regression model, the regression model equations are chosen by a better fitting R^2 value, but still keeping fairly simple equations. For evacuation traffic the regression model is a polynomial equation of order 2 with $R^2 = 0.7209$, which is identical to Equation 3. For the routine traffic the regression model is a polynomial equation of order 2 with $R^2 = 0.8236$, which is identical to Equation 4.

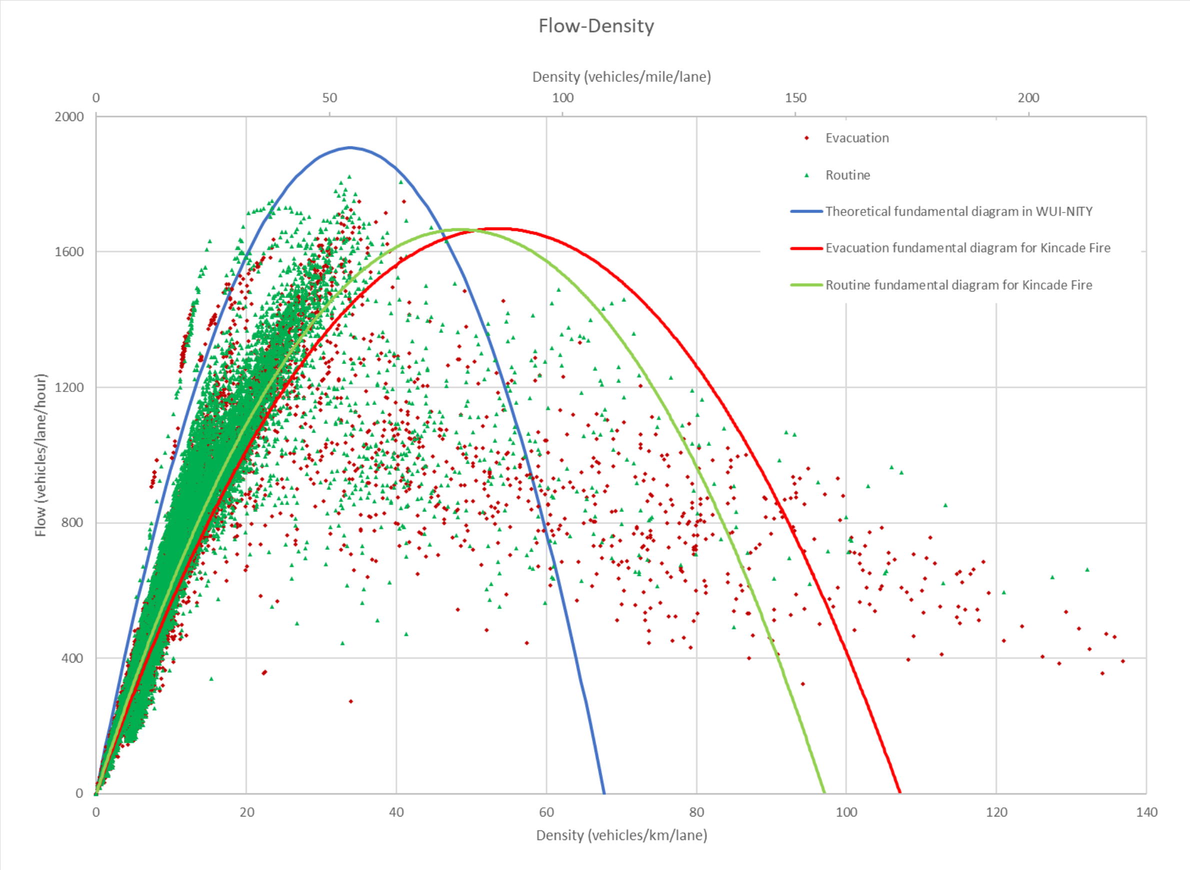


Figure 12 - Flow-Density relationship between theoretical, evacuation and routine traffic with best fitting regression model.

In the Flow-Density plot, see Figure 12, better fitting regression models that resulted in higher R^2-value have been identified. This is a polynomial equation of order 2 for both evacuation and routine traffic, the same regression model used in Figure 10, and therefore looks identical to previous flow-density plot. Other polynomial equations of higher order could provide with higher R^2-value, but that resulted in the flow increasing at the higher density levels, which would have no physical bearing.

Figure 13 shows the Speed-Density relationship for the theoretical fundamental diagram used in WUI-NITY and the extracted traffic data from PeMS. The extracted data is added as a scatter plot with a regression model applied to the scattered data. In the Speed-Density plot with regression model, the regression model equations are chosen by a better fitting R^2 value, but still keeping fairly simple equations. For evacuation traffic the regression model is a linear equation with R^2 = 0.8158, which is identical to Equation 5. For the routine traffic the regression model is a polynomial equation of order 2 with R^2 = 0.7332, see Equation 7.

$$v = -0.0024d^2 - 0.8316d + 112.15 \qquad \text{[Equation 7]}$$

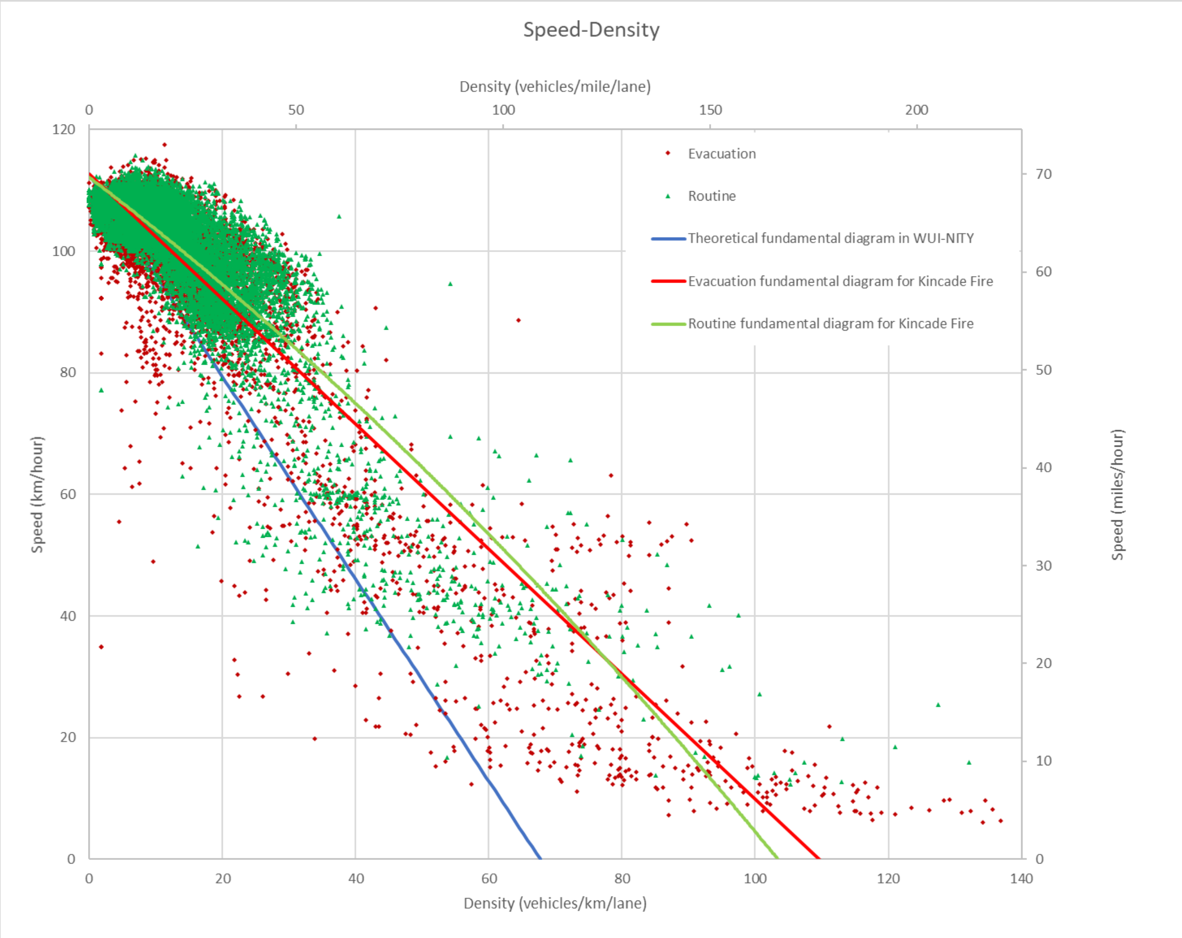


Figure 13 - Speed-Density relationship between theoretical, evacuation and routine traffic with best fitting regression model.

In the Speed-Density plot, see Figure 13, a better fitting regression models that resulted in a higher R^2-value have been identified. This is a for the routine traffic a polynomial equation of order 2 and for the evacuation traffic a linear equation. The linear equation for evacuation traffic had the same R^2-value as polynomial equation of order two, but the linear equation was favored because it is an equation of lower order. Other polynomial equations of higher order could provide with higher R^2-value, but that resulted in the speed increasing at the higher density levels, which would have no physical bearing. The regression model for the routine traffic while being a polynomial equation of order 2 is bending downwards. This does not fit the measured data in the higher density ranges but is instead favored for the large quantities of measured data in the lower density ranges.

To further compare the actual data with theoretical fundamental diagrams, Figure 14 shows the Flow-Density relationship for the theoretical fundamental diagram if presented as triangular trend (TRB, 2016) and the extracted traffic data from PeMS. The extracted data is added as a scatter plot with a triangular trend applied to the scattered data. The routine and evacuation triangular trends are not regression models based on all of the measured data, but a simple linear trend between the maximum measured values. For the extracted data the triangular trends are based on the (0,0) point in the diagram, the highest measured flow and corresponding density, as well as the highest measured density and corresponding flow. This gives each triangular trend two equations applicable in different density range. The density range is different for each triangular trend.

The evacuation traffic triangular trend equations are defined within the densities 0, x_d = 35 and x_{max} =137, see Equation 8.

The routine traffic triangular trend equations are defined within the densities 0, x_d = 34 and x_{max} =132, see Equation 9.

The theoretical triangular trend equations are defined within the densities 0, x_d = 22 and x_{max} =68, see Equation 10.

$$\begin{cases} Q = 49.8856d\ [0, x_d] \\ Q = -13.2758d + 2208.3\ [x_d, x_{max}] \end{cases} \quad \text{[Equation 8]}$$

$$\begin{cases} Q = 54.1229d\ [0, x_d] \\ Q = -11.7958d + 2221.53\ [x_d, x_{max}] \end{cases} \quad \text{[Equation 9]}$$

$$\begin{cases} Q = 85.778d\ [0, x_d] \\ Q = -41.686d + 2823.3\ [x_d, x_{max}] \end{cases} \quad \text{[Equation 10]}$$

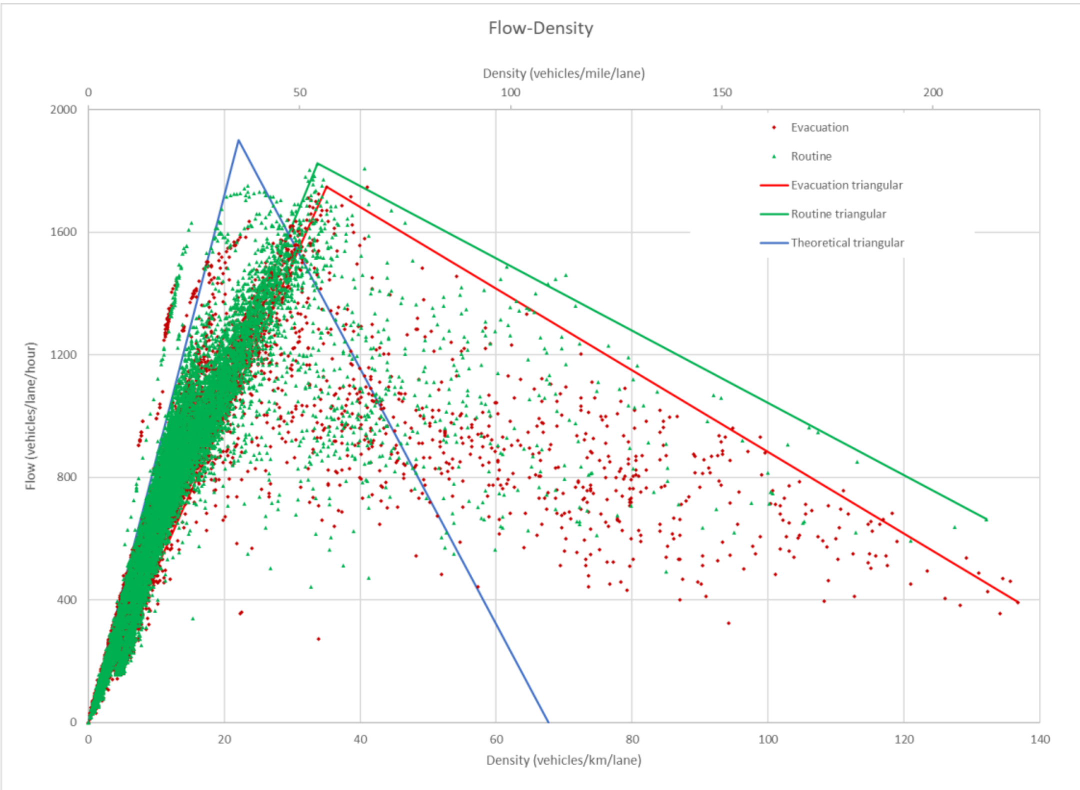


Figure 14 - Flow-Density relationship between theoretical, evacuation and routine traffic with triangular trends.

In the Flow-Density plot, see Figure 14, a triangular trend is applied to theoretical, routine and evacuation data. This is done with intent to adopt a similar approximation to what is often done in application of this type of data (TRB, 2016). The theoretical data is based on the HCM (TRB, 2016), where the base speed at capacity is ≈ 86 km/h (53.3 mph) with a capacity of 1900 vehicles/lane. The theoretical maximum density is still the same as previous theoretical plots at ≈ 67 vehicles/km/lane, but the density at which the maximum flow occurs at can be calculated with the new speed at capacity to ≈ 22 vehicles/km/lane, which is reduction from the previous ≈ 34 vehicles/km/lane.

6. Discussion

In this thesis, three objectives were set linked to the performance of V&V of the traffic component of the WUI-NITY platform to increase its calculation accuracy and reliability. First a set of verification tests were designed and developed with the traffic layer and macroscopic modelling in mind. Second, the tests were run in the simulator, results were analyzed and used to improve the testing procedure, then run again once more in an iterative loop until the tests were the most suitable one to evaluate the model and making sure simulation results were in line with hand calculations. Finally, a simple validation test was performed by comparing a core traffic component, i.e., flow-density and speed-density relationships with traffic evacuation data observed from the Kincade Fire.

The verification tests were created with the traffic layer in focus, but also on its interaction with the pedestrian and wildfire layers. The pedestrian layer was not run in the simulation given the scope of the current work. Not being able to run the pedestrian tests did not have an impact on the rest of this work, since the main focus here was on the traffic component. The verification tests created for the traffic layer and the interaction between traffic and fire layers performed relatively well, except for the tests that could not be run since they were not compatible with the macroscopic modelling approach adopted. A majority of the tests had no or small difference in result between the simulated and hand calculated results. Those that did showed a difference in results had a difference in the range of 0,5 – 8 %. The difference was caused by approximation in the implementation of the fundamental diagram, stall speeds and time-step approximations, with a general trend of longer run times resulting in bigger differences. This was expected since the hand calculation uses simple assumptions for its calculation, mostly relying on the distance-time-velocity relationship and a linear reduction of speed with increasing density.

The result from the validation test shows that the theoretical fundamental diagram currently adopted by WUI-NITY has a limitation in density ranges in comparison to the collected evacuation traffic data during the Kincade Fire. For the flow-density relationship this means that maximum flow is reached at low density and that the flow is reduced to 0 not much after the routine and traffic regression models reaches their maximum flow, in terms of density. The theoretical fundamental diagram peaks and drops in flow at a much lower density range than the fundamental diagram for routine and evacuation traffic. In contrast, maximum flow for the theoretical fundamental diagram is higher than the actual flow evacuation and routine data. In real cases, this could be caused by several factors, e.g., the presence of smoke during the evacuation, limiting drivers' visibility (Wetterberg, et al., 2021). For the speed-density relationship this means that the theoretical speed is reduced faster than the actual evacuation traffic data, for both evacuation and routine. The speed for routine traffic seems to be overall higher than evacuation traffic at corresponding densities. While the theoretical speed is reduced to 0 when congestion levels are too high, the routine and evacuation speeds never seem to get reduced to 0 no matter how much the density increases but stays at minimum speed instead. This could be caused by the nature of the data, which is gathered every 5 minutes and creates aggregated values that could cause extreme density levels with stop in traffic flow and speed to become seemingly invisible in the analyzed measured data.

In future research, a more complete validation of this core traffic component is needed for the individual fundamental diagram for each road type commonly used. In addition, verification testing is needed for the tests was not able to run in this iteration, such as route choice, pedestrian movement, or human response behaviour. Additional tests need to be designed for the pedestrian and more interaction tests between the wildfire layer and the pedestrian and traffic layers. For validation of the traffic component, more components need to be validated, such as variables linked to traffic demand and traffic assignment. An example is route choice testing, allowing to get more accurate representable driving behaviour for people driving through wildfire (e.g., what route they prefer, impact of evolving fire conditions what discourage them from making certain decision in traffic, how other road users affect their decision making etc.).

In the gathering of traffic data, the occupancy had to be converted by using Equation 1. In this equation, the average vehicle length needs to be assumed. In conversion performed in this validation, the average vehicle was assumed to be 4.5 m. This assumption is presuming that everyone drives a vehicle of this size, while that actually may not be the case. It has been seen before in wildfire and hurricane evacuations that the average vehicle length is higher due to people taking boat trailers with them, caravans, campers, trucks, vans, etc. (Maghelal, et al., 2017) (Wu & Lindell, 2012). With longer average vehicle length, the number of vehicles that can fit in 1 km is reduced, resulting in a reduction in vehicles/km/lane. For the fundamental diagram this means that measured evacuation traffic data for both speed-density and flow-density relationships gets moved to the left in the plots closer to the theoretical data. For flow-density plot this means that the evacuation traffic peak flow is lower than the routine traffic peak flow since with lower density follows a reduction in flow.

The gathered data for forming the routine and evacuation fundamental diagram is heavily depending on the measurement system implemented and that the data is accurate and correct. If these detectors are not working correctly and provide misinformation, then the gathered data used is not representing the events that unfolded. The detectors are outside and have to endure all sorts of weather condition, wearing down the detectors until they break down and no longer produce good or accurate measurements. The PeMS also provides the user with data quality and detector health, regarding if the detector is in good health or not, and if it as a result can provide accurate measurement. PeMS can detect malfunctioning detectors based on algorithms using measured data from previous day and neighboring detectors. The wrongly measured data gets removed from the database and new interpolated data from neighboring detectors gets added to fill the empty time step, with apparently high accuracy (Chao, 2003).

The gathered data using 5 minutes interval can contain extreme peaks of density that do not represent the actual traffic congestions during an evacuation. Such data could be generated from a road incident or a failing detector measurement. Road incidents occurring at the detector location or further downstream can cause an artificial increase in density if multiple lanes suddenly have to merge to get pass the incident. These peaks could happen only a few times causing a displacement for the trendline applied to the measured data. A more accurate way to handle the gathered data would be to remove the outliers unless they are still within defined limits. However, to know if a measured data with high values is caused by an incident or a failing measurement is difficult when analyzing the gathered data. When checking a detector and timestamp, the PeMS notifies the user if there were any incidents during the time period searched around the location. It can display incident start time, duration, location, and what type of incident it was (e.g., traffic collision, traffic hazard, hit and run, car fire). The incidents that did occur at the time and locations used in the routine and evacuation traffic fundamental diagram happened on off- and onramps to the US101, and not seemingly on the US101 itself. It is plausible that the incidents had an effect on the surrounding traffic, but to what extent is unknown. In the documentation for PeMS in the section describing Incident analysis, it is written *"What was its effect on the traffic at this location? A traffic analyst at the Traffic Management Center (TMC) can use PeMS's plotting tools to get the answer"* (Chao, 2003). No traffic analyst or tools at TMC were available when making this validation test. A way to improve the gathering of traffic data in case of negative impact on traffic flows caused by an incident could be to use individual lane data instead of average lane data. This could let the user spot potential impact on the traffic from an incident more easily and discard the data if needed.

Another useful regression model to use when representing the measured flow and density data for routine and evacuation traffic could be two linear trends to form a triangular shape. This could be a better fit, since the polynomial regression model of order 2 visually do not accurate represent the measured data. The measured data in the lower density during free-flow state can visually be seen to take a linear shape. After the free-flow state has been passed, the data becomes scattered in a wide range, but seem to be focused back together again the higher the density gets increased. Having multiple lines, the free-flow state and the flow corresponding to maximum density could give more accurate representations of the measured data. From here the line with higher R^{2-} value can be selected.

A similar case comparing non-emergency routine traffic with evacuation traffic has been made and how traffic characteristics changed in regular traffic when evacuating from hurricanes (Dixit & Wolshon, 2014). In this work, traffic data was collected from evacuations during the Hurricanes Ivan (2004), Katrina (2005) and Gustav (2008). The evacuation data was compared to routine data gathered from six different stations on the I-10 in New Orleans, Louisiana with a 15-minute interval for aggregated speed and flow. The I-10 used to gather traffic data is similar to the US101 used in the Kincade Fire evacuation, in regard to having a speed limit of 70 mph and 2 lanes in the more rural areas and 3-4 lanes in the more urban areas. Figure 15 is a Flow-Density graph for routine and evacuation traffic collected during Hurricanes Ivan, Katrina and Gustav at one of the data gathering stations at Loyola. The gathered data from the hurricane evacuation can be compared to the Kincade Fire case study, see Figure 14. It can be observed that the routine and evacuation data follow a straight line together during free-flow state up to peak flow, then the flow decreases with increasing flow. The free flow state in the Kincade fire for both routine and evacuation traffic reached higher peak flows at higher density and with the peak flow being 300-400 vehicles/lane/hour more than that of the Hurricane data. The maximum measured density for the Kincade fire is higher almost by 90 vehicles/mile/lane more than the Hurricane. The Hurricane data set have less measurements to compare with compared to the Kincade Fire data set, but a similarity that can be observed through the measured data is that the routine traffic can achieve a higher flow than the evacuation traffic.

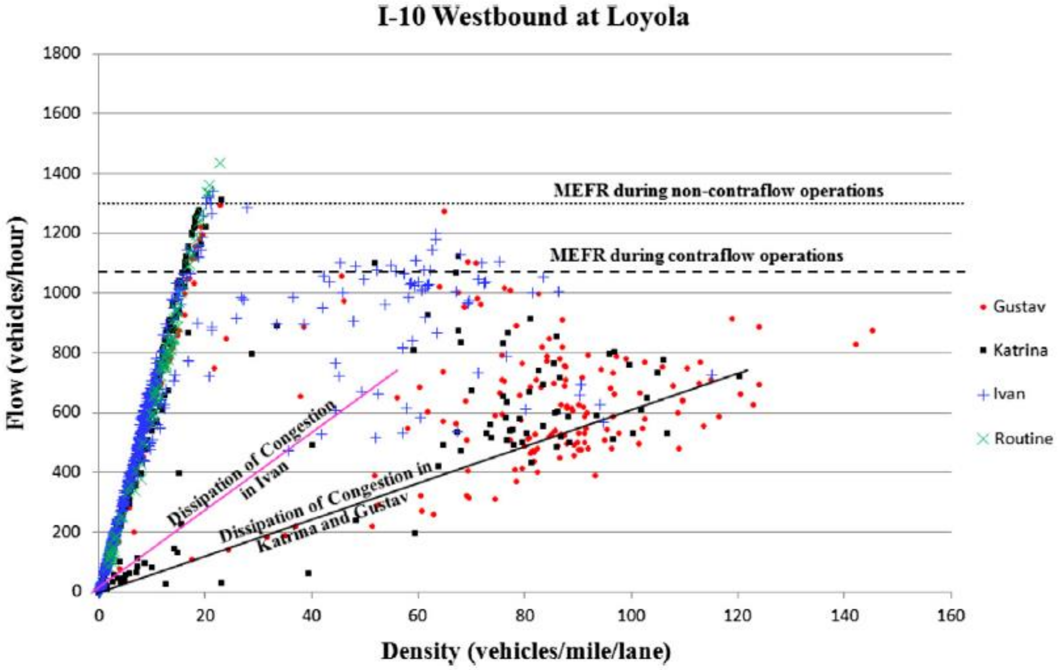


Figure 15 - Flow density graph for routine non-emergency traffic and evacuation during Hurricanes Ivan, Katrina and Gustav. Figure taken from (Dixit & Wolshon, 2014)

7. Conclusion

This thesis presents the verification and validation performed on the simulation platform under development WUI-NITY to analyze a core traffic component, the fundamental diagrams (i.e., the flow-density and speed-density relationships) which is one of the central elements of the model. Verification and validation of calculation methods are crucial to grant them credibility through accurate predictions and reliable reconstruction of the course and consequence of an emergency event. To perform the verification on the traffic components of WUI-NITY, a set of verification tests were designed and run through application in WUI-NITY. The results were analyzed and used to improve and refine the tests to run through WUI-NITY again until acceptable results were produced with low difference between simulation and expected hand calculations. To perform the validation of the fundamental diagrams, the database Caltrans PeMS were selected for gathering real life evacuation and routine traffic data. It was used to extract relevant traffic data during the well-documented evacuation of the Kincade Fire 2019 in Sonoma County, California. By converting and normalizing the extracted traffic data and applying a regression model to the measured data, two new fundamental diagrams were created, one for the evacuation traffic and one for the routine traffic. The created fundamental diagrams were compared to the theoretical fundamental diagram coded in WUI-NITY and produced results in terms of differences in peak flows, limitation in used density ranges and minimum speed traffic reaches during congestion. These differences can be used as a basis to improve upon the tested core component, thus leading to a successful verification and validation testing. The model testing could handle the application of verification tests in a majority of cases constructed and produce useful results. Since the validation testing performed revolved around fundamental diagrams for vehicles in traffic, the verifications test for pedestrians were created but not tested through applications with the model. In addition, a few verification tests could not be tested through application of the model since the nature of their component are better suited for microscopic models, while WUI-NITY uses macroscopic model. Additional research is needed on validation testing for other commonly used road types to produce a complete set of validated fundamental diagrams. In addition, other core components need validation testing, such as route choice decision making in traffic.

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Annex A
Reporting Template

Test XX. Name of the test

Brief description of the test in accordance with the original text and table presented in this document.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   ____

   ____

   ____

   ____

   ____

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)

   ____

   ____

   ____

   ____

   ____

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   ____

   ____

   ____

   ____

   ____

4. How have the behaviours been represented?

   [ ] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

   ____

   ____

   ____

   ____

   ____

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [ ] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED]

   If YES, how was the variation in results assessed?

   ____

   ____

   ____

   ____

   ____

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED]

   If YES, explain which factors within the configuration were modified and how:

   ____

   ____

   ____

   ____

   ____

   Describe how you performed the user's actions requested in the test description:

   ____

   ____

   ____

8. Results

Present here the results in line with the expected results of the test. Results can be:

— Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

— Flows: present this result with an accuracy in the order of two digits in people/s·m or vehicles/hr*km and compare it with the expected result (difference should be presented in %).

— Densities: present this result with an accuracy in the order of two digits in people/m^2 or vehicle/km*lane and compare it with the expected result (difference should be presented in %).

— Speeds: present this result with an accuracy in the order of two digits in m/s and compare it with the expected result (difference should be presented in %).

— Relationship between time (s), flows (people/s·m or vehicles/hr*Km) and densities (people/m^2 or vehicle/km*lane): present the simulated relationship and compare it with the expected result (difference should be presented in a plot).

— Evacuation time curve: Present this curve with people or vehicles in the x axis and time (in s) in the y axis).

— Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.

— Graphic visualization: present screenshot(s.) of the simulation results (e.g. travel paths, agent location over time, etc.).

Present the results using the requested methods of analysis of results associated with the test. Along with the average results, the model testers should also present the range of results obtained (e.g. 95^{th} percentile) in case of multiple simulations.

Annex B
Verification testing report

Test T.1a. Uni-directional single vehicle flow

Brief description of the test in accordance with the original text and table presented in this document.

Testing that a single vehicle will drive with an assigned free flow speed in one direction that corresponds to one road type.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

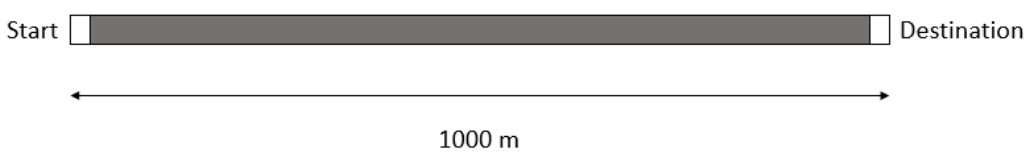
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The vehicle drives on a road segment that has an assigned road type to it, which has a given speed limit (e.g., residential road 50 km/h, highway 120km/h). If possible, the vehicle is assumed driving at the highest possible speed the road type allows. If there are more vehicles, the actual speed limit is reduced relative to the number of vehicles on the road using the Lighthill-Whitham-Richards model.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A road with a single carriageway and a single lane for a length of 1000 m. The road type corresponds to a speed limit of 90 km/h.

3. Scenario configuration

Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

If possible, the vehicle drives at the highest possible speed the road type allows. If there are more vehicles, the speed will get reduced in relation to the number of vehicles on the road.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

   If YES, explain which factors within the configuration were modified and how:

   Changing the road type to correspond to a speed limit on the lower end as well as on the higher end.

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

Vehicles have default settings with no acceleration or deceleration.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

The simulated result for 30 km/h was 122 s and the expected result was 122 s, a difference of 0 %.

The simulated result for 50 km/h was 73 s and the expected result was 73 s, a difference of 0 %.

The simulated result for 70 km/h was 52 s and the expected result was 52 s, a difference of 0 %

The simulated result for 90 km/h was 40 s and the expected result was 41 s, a difference of 2 %. = (41-40) / 41

The simulated result for 110 km/h was 33 s and the expected result was 33 s, a difference of 0 %.

Test T.1b. Uni-directional single vehicle flow

Brief description of the test in accordance with the original text and table presented in this document.

Testing that a single vehicle will drive with an assigned free flow speed in one direction that corresponds to multiple road type.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

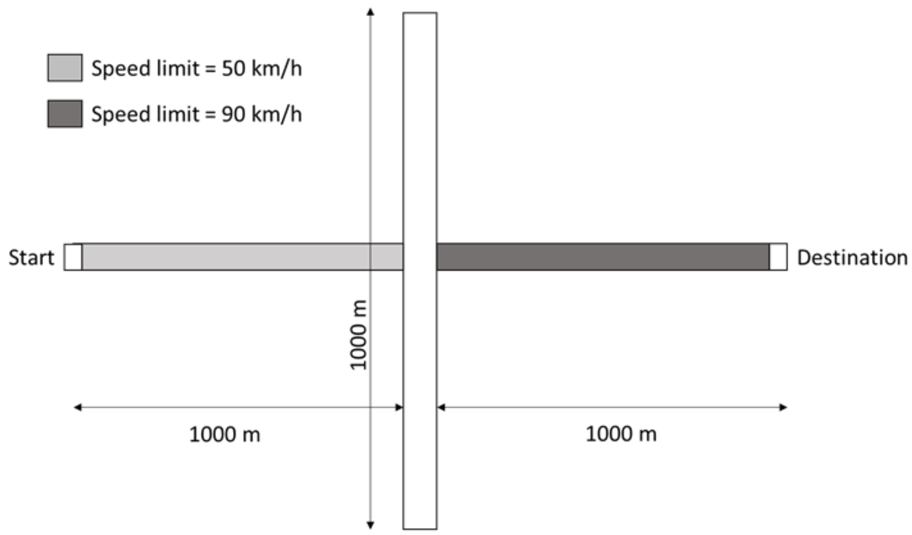
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The vehicle drives on a road segment that has an assigned road type to it, which has a given speed limit (e.g., residential road 50 km/h, highway 120km/h). If possible, the vehicle is assumed driving at the highest possible speed the road type allows. If there are more vehicles, the actual speed is reduced in relation to the number of vehicles on the road using the Lighthill-Whitham-Richards model.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



A road with a single carriageway and a single lane for a length of 1000 m + 1000 m. The first part has a road type that corresponds to a speed limit of 50 km/h, and the second part a road type that corresponds to a speed limit of 90 km/h.

3. Scenario configuration

Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

If possible, the vehicle drives at the highest possible speed the road type allows. If there are more vehicles, the speed will get reduced in relation to the number of vehicles on the road.

4. How have the behaviours been represented?

[x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

[ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

[ ] Blind

[x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

If YES, explain which factors within the configuration were modified and how:

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

Vehicles have default settings with no acceleration or deceleration.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

The simulated result was 114 s and the expected result was 113 s, a difference of 1 %. = (114-113) / 113.

Test T.2. Background traffic

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the background traffic, people on the road not actively evacuating, has an impact on the vehicle flow.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [x] Yes, feature/behaviour implicitly represented

   [ ] Partially

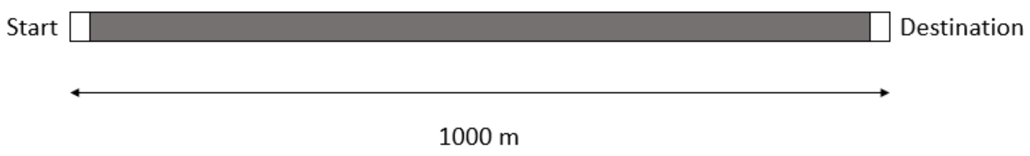
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The background traffic is represented using a vehicle density modifier which is implemented with a linear uniform distribution, which can be specified during the evacuation.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A road with a single carriageway and a single lane for a length of 1000 m. The road type corresponds to a speed limit of 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   A background traffic is implemented that reduces the flow capacity on the road by 50 %, forcing a single evacuating vehicle to reduce its speed accordingly.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

   If YES, explain which factors within the configuration were modified and how:

   Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.
Vehicles have default settings with no acceleration or deceleration.
The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

- Requested result: Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

The simulated result was 81 s and the expected result was 80 s, a difference of 1 %. = (81-80) / 80.

Test T.3. Change in carriageway configuration

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the carriageway configuration has an impact on the vehicles speed and that it changes accordingly.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

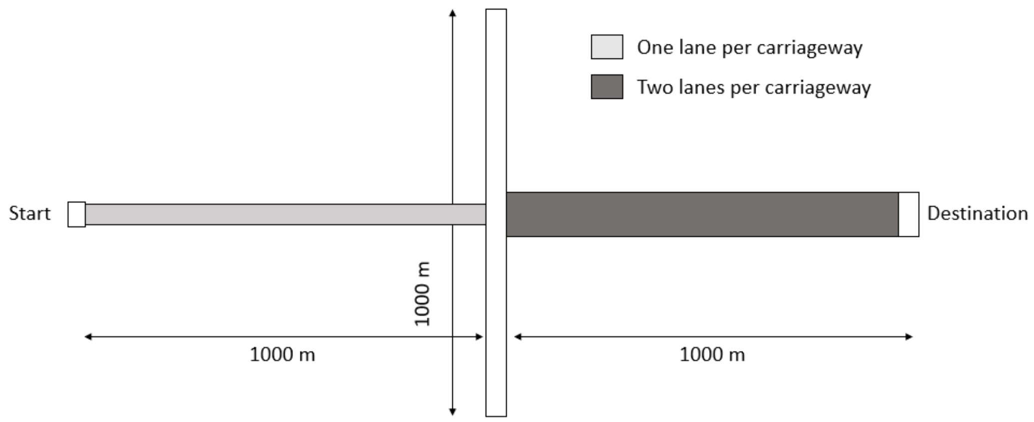
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The vehicle drives on a road segment that has an assigned road type to it, which has a given speed (e.g., residential road 50 km/h, highway 120km/h). If possible, the vehicle will drive at the highest possible speed the road type allows. If there are more vehicles, the actual speed is reduced in relation to the number of vehicles on the road using the Lighthill-Whitham-Richards model.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A road with a single carriageway for a total length of 1000 m + 1000 m with an unsignalized intersection. The initial 1000 m segment of the road has one lane per carriageway, while the following 1000 m segment has two lanes per carriage way. The associated speed limits in the two road segments change accordingly. The road type should correspond to a speed limit equal to 90 km/h.

3. Scenario configuration

Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

One vehicle drives on the road segment with an assigned free flow speed corresponding to the speed limit. If possible, the vehicle drives at the highest possible speed the road type allows. If there are more vehicles, the actual speed will get reduced in relation to the number of vehicles on the road. When the vehicle density reaches max capacity, the speed gets set to a limited speed which is calculated through modelling assumptions to be 1,071148 km/h, instead of a set speed limit of 1 km/h.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

   If YES, explain which factors within the configuration were modified and how:

   The test is repeated using 5 different vehicle density levels linear from 1 vehicles/km/lane to the vehicle density corresponding the vehicles being stopped considering the portion of the road with smaller capacity. The densities used were 1, 12, 25, 38 and 50 vehicles/km/lane.

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

Vehicles have default settings with no acceleration or deceleration.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

The simulated result for each of the 5 vehicle density levels are D1 = 81 s, D2 = 96 s, D3 = 127 s, D4 = 214 s, D5 = 3423 s.

The expected result for each of the 5 vehicle density levels are D1 = 81 s, D2 = 96 s, D3 = 127 s, D4 = 214 s, D5 = 3660 s.

The difference between the simulated and expected result for each of the 5 vehicle density levels are D1 = 0 %, D2 = 0%, D3 = 0 %, D4 = 0%, D5 = (3660-3423)/3660 = 6 %.

Test T.4. Relationship between speed-density and flow-density

Brief description of the test in accordance with the original text and table presented in this document.

Testing speed-flow-density relationships and plotting the results.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

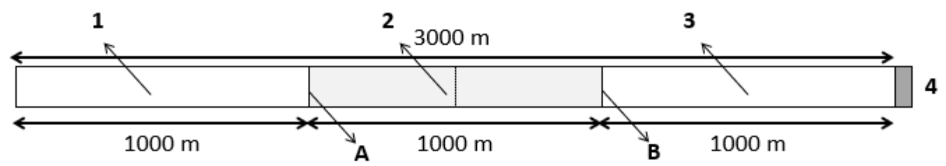
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The traffic flow is simulated through a speed-flow-density relationship. Speed *v* is calculated as the travel distance covered divided by time (considering a given time-step). Density *d* is intended as the number of vehicles in each unit road. Flow *q* is the number of cars per unit of time. The model adopted is the Lighthill-Whitham-Richards model (LWR model).

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is road segment considering movement on a single carriageway with a single lane for a total of 3000 m divided in three zones of equal length with a road type corresponding to a speed limit of 70 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   Vehicles are uniformly distributed over the entire road segment with an initial free flow speed equal to the speed limit. Placement of the last vehicle in zone 2 should be placed close to line A. Measure the time it takes from line A to line B and estimate the associated driving speed. Measure the average vehicle flows in line B from simulation start until the last vehicle in zone 2 arrives to line B. Vehicle densities in zone 2 are recorded when the last vehicle in zone 2 reaches the centre of zone 2.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

   If YES, explain which factors within the configuration were modified and how:

   The test was repeated for each of the five vehicle density levels linear from 1 vehicle/km/lane to a vehicle density leading to stopped vehicles on the road segment. The densities used were 1, 19, 38, 56, and 75 vehicles/km/lane.

   Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.
Vehicles have default settings with no acceleration or deceleration.
Results are presented in relation to different time intervals adopted for the estimation of flow, people
densities and walking speeds.
The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

Requested result:

- Relationship between time (s), flows (people/s·m or vehicles/hr*Km) and densities (people/m^2 or vehicle/km*lane): present the simulated relationship and compare it with the expected result (difference should be presented in a plot).

The expected flow vehicles/lane/hour for the different densities are at D1 = 69, D2 = 998, D3 = 1331, D4 = 1035 and D5 = 75. Calculated as a group that evacuates the area at the same time. The number of vehicles is divided by the time it took to drive the distance multiplied with 3600.

The expected speed km/h for the different densities are at D1 = 69, D2 = 53, D3 = 35, D4 = 18 and D5 = 1. Calculated as a group that evacuates the area at the same time.

The simulated flow-density and speed density relationship are the theoretical curves that changes with increasing density, see Figure 1 and Figure 2

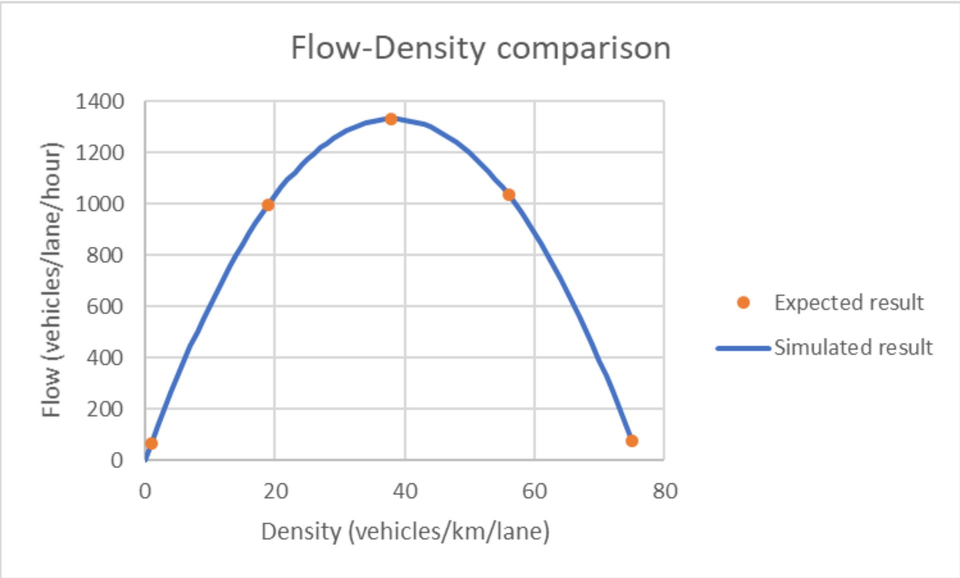


Figure 16 - Flow-density comparison between expected and simulated results.

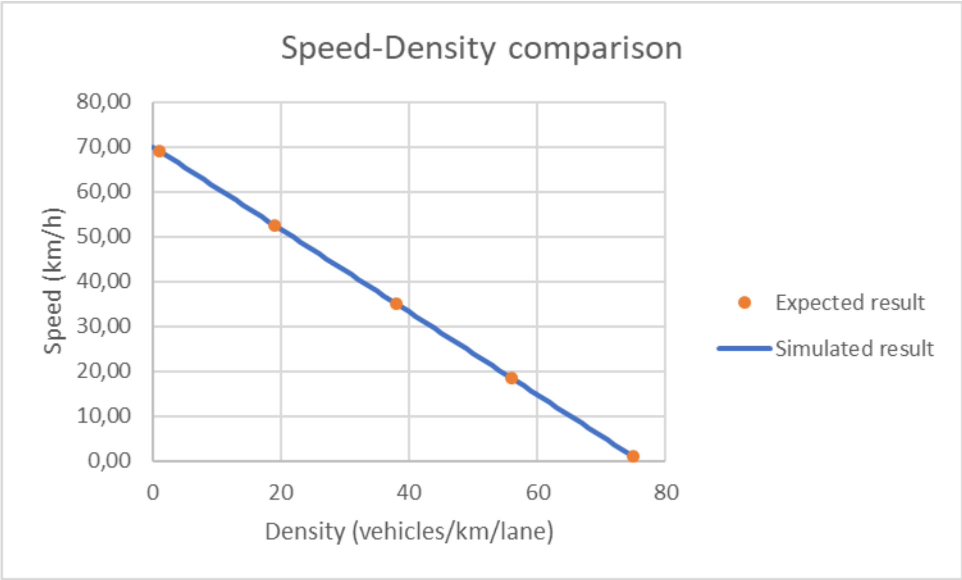


Figure 17 - Speed-density comparison between expected and simulated results.

Test T.5. Vehicle speed reduction in reduced visibility conditions

Brief description of the test in accordance with the original text and table presented in this document.

Testing reduced visibility and its effect on vehicle speed reduction.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

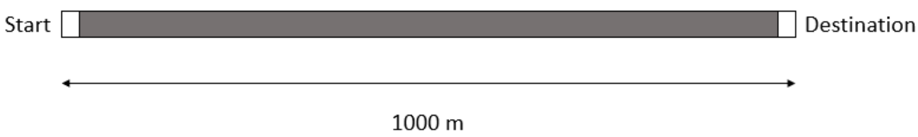
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The model uses a relationship between vehicle speed and visibility corresponding to optical density per m. The relationship is taken from Wetterberg et al. report on individual driving behaviour in wildfire smoke (Wetterberg, et al., 2021).

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is a road on a single carriageway with a single lane for a total length of 1000 m. The road type should correspond to a speed limit equal to 70 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   The scenario is one vehicle driving from start to destination and adapting its speed in accordance with the vehicle density levels as well as the visibility levels.

4. How have the behaviours been represented?

[x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

[ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

[ ] Blind

[x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

If YES, explain which factors within the configuration were modified and how:

The test was repeated for each of the five vehicle density levels linear from 1 vehicle/km/lane to a vehicle density leading to stopped vehicles on the road segment. This together with five visibility levels linear from visibility corresponding to an optical density of 0 m^{-1} to 0,20 m^{-1} for each vehicle density level. The densities used were 1, 19, 38, 56, and 75 vehicles/km/lane.

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.
Vehicles have default settings with no acceleration or deceleration.
The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

Simulated result (s)	D1	D2	D3	D4	D5
No Smoke	52	68	102	194	3414
Visibility level 1	80	105	157	294	3479
Visibility level 2	112	146	217	399	3514
Visibility level 3	137	179	265	482	3530
Visibility level 4	168	219	321	576	3544

Expected result (s)	D1	D2	D3	D4	D5
No Smoke	52	69	103	195	3600
Visibility level 1	81	106	159	301	3600
Visibility level 2	112	147	221	419	3600
Visibility level 3	138	181	272	515	3600
Visibility level 4	168	221	332	629	3600

Differences in results (%)	D1	D2	D3	D4	D5
No Smoke	0	1.	1	0.5	5
Visibility level 1	1.	0.9	1.	2	3
Visibility level 2	0	0.7	2	5	2
Visibility level 3	0.7	1.	3	6	2
Visibility level 4	0	0.9	3	8	2

Test T.6. Flow at destination

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the flow of vehicles does not exceed the maximum flow rate.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

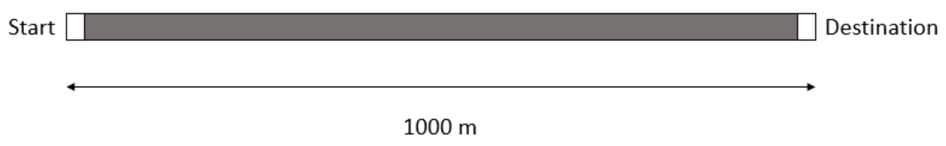
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The flow at destination is a boundary condition set up in line with the Lighthill-Whitham-Richards model. It creates an artificial density on the last stretch of the road to avoid non-realistic flows at the edge of the scenarios.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is a road with a single carriageway and a single lane for a total length of 1000 m. The road Type corresponds to a speed limit equal to 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   Vehicles are added and distributed on the entire road segment with an initial free flow speed equal to the speed limit.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

   If YES, explain which factors within the configuration were modified and how:

   The test was repeated for each of the five vehicle density levels linear from 1 vehicle/km/lane to a vehicle density leading to stopped vehicles on the road segment.

   The densities used were 1, 19, 38, 56, and 75 vehicles/km/lane.

   Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.
Defining the maximum flow capacity in relation to the underlying assumptions used during the
development of the model. Document the assumptions adopted in the representation of the flows (emergent
flow or user-defined).
The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

Requested result:

- Flows: present this result with an accuracy in the order of two digits in people/s·m or vehicles/hr*km and compare it with the expected result (difference should be presented in %).

The maximum flow threshold that cannot be exceeded is 3600 vehicles/hour/lane.

The expected flow vehicles/lane/hour for the different densities are at D1 = 89, D2 = 1282, D3 = 1706, D4 = 1319 and D5 = 75. Calculated as a group that evacuates the area at the same time. The number of vehicles is divided by the time it took to drive the distance multiplied with 3600 s.

The simulated maximum flow over the entire period is 3600 vehicles/hour/lane.

Test T.7. Group evacuation

Brief description of the test in accordance with the original text and table presented in this document.

Testing to see that multiple vehicles that evacuates from the same household evacuate together.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

   [x] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

Test T.8. Lane changing/overtaking

Brief description of the test in accordance with the original text and table presented in this document.

Testing that a faster moving car will change lane and overtake a slower moving car.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

   [x] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

Test T.9. Acceleration/deceleration

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the vehicle can both accelerate and decelerate when starting and stopping.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

   [x] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

Test T.10. Road accident

Brief description of the test in accordance with the original text and table presented in this document.

Testing that a road accident event stops or hinders the traffic flow.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [x] Yes, feature/behaviour implicitly represented

   [ ] Partially

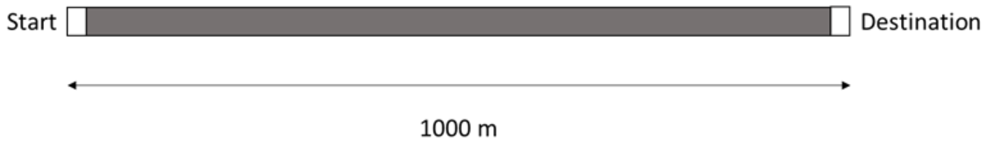
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The model can include events that occurs during the simulation between the fire spread evolution and evacuation interaction.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is a road with a single carriageway and a single lane for a total length of 1000 m. The road type correspond to a speed limit equal to 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   A vehicle drives with free flow speed to its destination. The event that triggers the road accident gets activated after a certain at which the traffic is stopped or slowed down for a period of time or until the the vehicle reaches the destination.

4. How have the behaviours been represented?

[x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

[ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

[ ] Blind

[x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

If YES, explain which factors within the configuration were modified and how:

The stall speed is changed to 0 km/h and a stall timer is added to ensure the simulation stops if the vehicles Have been evacuation for 3600 s.

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

Vehicles have default settings with no acceleration or deceleration.

The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

Sub-case with stall speed of 1 km/h:

The simulated result is 2724 s.

The expected result is 2722 s.

The difference of the results is negligible (2724-2722)/2722 = 0,07 %

Sub-case with stall speed of 0 km/h:

The simulated result is 2724 s.

The expected result is 2722 s.

The difference of the results is 0 %.

Test T.11. Intersection

Brief description of the test in accordance with the original text and table presented in this document.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [x] Partially

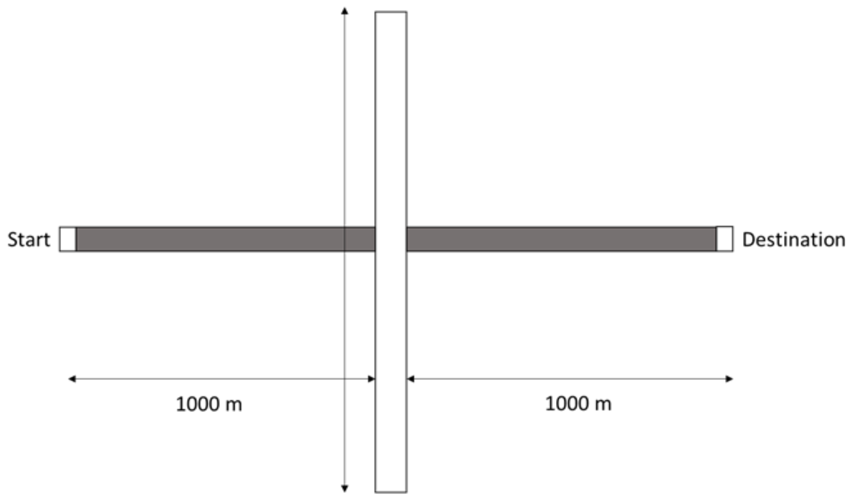
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The sub-model tests the functionality of a merging flow at an intersection.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A geometry with a single carriageway and a single lane for a total length of 1000 m + 1000 m with an unsignalized intersection and an intersection road of reasonable length. The road type before and after the intersection should correspond to a speed limit equal of 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

A vehicle drives with assigned free flow speed to the destination while traversing the intersection.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

   If YES, explain which factors within the configuration were modified and how:

Describe how you performed the user’s actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

Vehicles have default settings with no acceleration or deceleration.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

The simulated result is 81 s.

The expected result is 81 s.

There is no difference between the results.

Test T.12. Forced Destination

Brief description of the test in accordance with the original text and table presented in this document.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   Route choice is computed by adopting the open source route planning tool Itinero[3]. The destinations of the cars within the traffic model are user-defined. Destination preferences can be set by the user, or by default, if there are several available destinations, the vehicles select the closest destination as an initial target. The user can also draw areas on the GUI for choosing destinations which override the default nearest option.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)

   A road with a single carriageway and a single lane with an intersection leading to two different destinations for a total length of either 1000 m, or 2000 m with a road type corresponding to a Speed limit equal to 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   One vehicle drives with assigned free flow speed. The vehicle is forced to drive to Destination B since it is further away than Destination A.

[3] https://www.itinero.tech/

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

   If YES, explain which factors within the configuration were modified and how:

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.

The simulated result is 1 vehicle arrives at Destination B.

The expected result is 1 vehicle arrives at Destination B.

Both results have the vehicle arrive at the same destination.

Test T.13. Destination choice in traffic

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the vehicle makes the correct destination choice based on route condition (shortest, fastest, other condition).

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

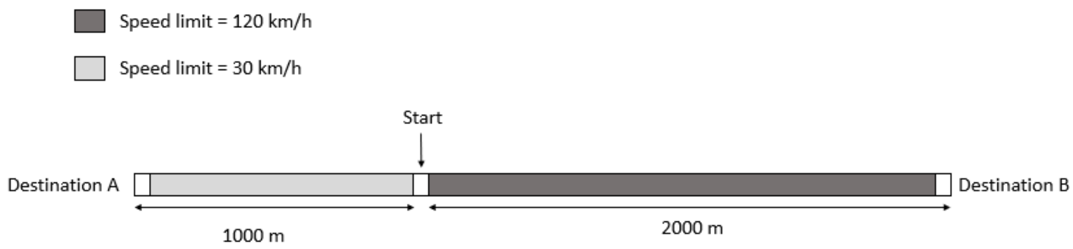
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   Route choice is computed by adopting the open source route planning tool Itinero. The destinations of the cars within the traffic model are user-defined. Destination preferences can be set by the user, or by default, if there are several available destinations, the vehicles select the closest destination as an initial target. The user can also draw areas on the GUI for choosing destinations which override the default nearest option.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A road with a single carriageway and a single lane with an intersection leading to two different destinations for a total length of either 1000 m, or 2000 m. The road leading to Destination A corresponds to a speed limit equal to 30 km/h. The road leading to Destination B corresponds to a speed limit equal to 120 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

One vehicle with an assigned free flow speed corresponding to the road types drives toward either Destination A or B depending on implemented route condition (e.g. fastest, closest, visibility, other condition) and is by user pre-defined.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

   If YES, explain which factors within the configuration were modified and how:

   The destination choice is changed between the available options of closest destination or fastest destination, smoke on the route or any other condition.

Describe how you performed the user's actions requested in the test description:

Vehicles have default settings with no acceleration or deceleration.
The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

- Requested result: Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).
- Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.

The simulated result for the shorter and slower route is 122 s and the vehicle arrives at Destination A.

The expected result for the shorter and slower route is 122 s and the vehicle arrives at Destination A.

There is no difference between the results.

The simulated result for the longer and faster route is 61 s and the vehicle arrives at Destination B.

The expected result for the longer and faster route is 61 s and the vehicle arrives at Destination B.

There is no difference between the results.

Test T.14. Route choice in traffic

Brief description of the test in accordance with the original text and table presented in this document.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

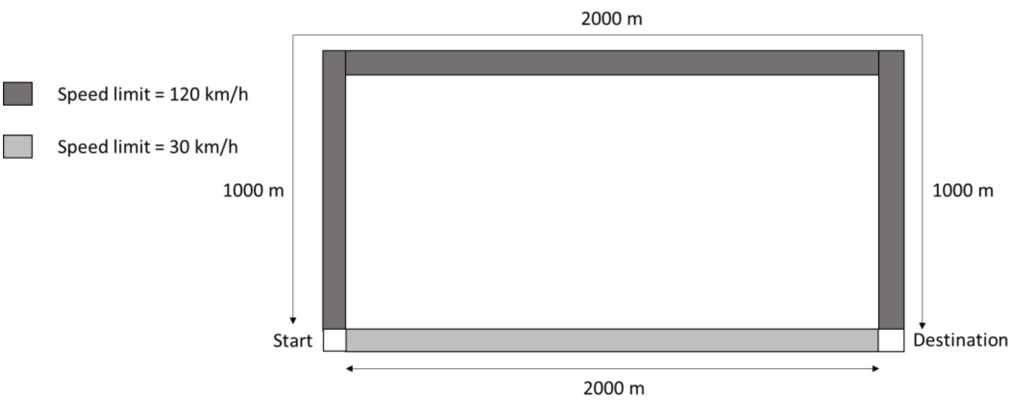
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   Route choice is computed by adopting the open source route planning tool Itinero. The destinations of the cars within the traffic model are user-defined. Destination preferences can be set by the user, or by default, if there are several available destinations, the vehicles select the closest destination as an initial target. The user can also draw areas on the GUI for choosing destinations which override the default nearest option.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is a road with a single carriageway and a single lane from a starting point connecting two separate roads leading to the same destination for a total length of either 4000 m or 2000 m. The road type for the longer route should correspond to a speed limit equal to 120 km/h. The road type for the shorter route should correspond to a speed limit equal to 30 km/h.

3. Scenario configuration

Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

One vehicle with an assigned free flow speed corresponding to the road types drives toward the Destination on the longer or shorter route depending on implemented route condition (e.g. fastest, closest, visibility, other condition) and is by user pre-defined.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

   If YES, explain which factors within the configuration were modified and how:

   The destination choice is changed between the available options of closest destination or fastest destination, smoke on the route or any other condition.

Describe how you performed the user's actions requested in the test description:

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

- Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.

The simulated result for the longer and faster route is 123 s.

The expected result for the longer faster route is 122 s.

The difference between the results is (123-122) / 122 = 0,8 %

The simulated result for the shorter and slower route is 245 s.

The expected result for the shorter and slower route in 243 s.

The difference between the results is (245-243) / 243 = 0,8 %

Test T.15. Vehicle demand vs arrival distribution

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the number of vehicles arriving at the Destination is the same as the implemented number of cars in the traffic model-

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [x] Yes, feature/behaviour implicitly represented

   [ ] Partially

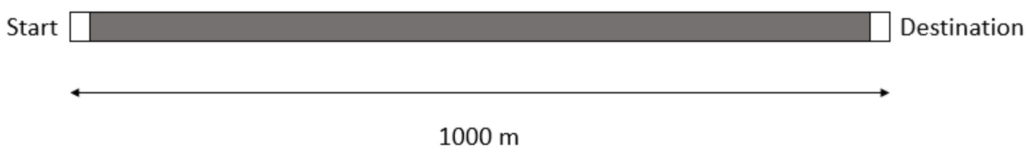
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The traffic model first reads information from the pedestrian model concerning the arrival of occupied vehicles over time into the traffic nodes. The simulated cars can be occupied by 1-5 passengers and is defined in relation to the size of the households approaching each traffic node. Each household is assumed to evacuate using one car by default, but the user can configure a probability distribution of cars leaving the household if there is more than one person per household.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is a single carriageway with a single lane for a total length of 1000 m. The road type corresponds to a speed limit equal to 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   The implemented number of vehicles drives with an assigned free flow speed corresponding to the speed limit driving to the Destination.

4. How have the behaviours been represented?

[x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

[ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

[ ] Blind

[x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] YES

If YES, explain which factors within the configuration were modified and how:

Changing the number of vehicles implemented in the test to 2, 50 and 100.

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

Requested result:

Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.The number of implemented vehicles is 2:

The simulated number of vehicles arriving at the Destination is 2.

The expected number of vehicles arriving at the Destination is 2.

There is no difference between the results.

The number of implemented vehicles is 50:

The simulated number of vehicles arriving at the Destination is 50.

The expected number of vehicles arriving at the Destination is 50.

There is no difference between the results.

The number of implemented vehicles is 100:

The simulated number of vehicles arriving at the Destination is 100.

The expected number of vehicles arriving at the Destination is 100.

There is no difference between the results.

Test WT.1. Route loss

Brief description of the test in accordance with the original text and table presented in this document.

Testing that if a route to a Destination is loss due to an event caused by the wildfire, another route will be used to reach the Destination.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

   [x] No, this feature/behaviour cannot be represented

   If you answered “No”, the test report is completed here. If you answer “YES” or “Partially”, explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

Test WT.2. Lane reversal

Brief description of the test in accordance with the original text and table presented in this document.

Testing that the activation of function for lane reversal works as intended.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

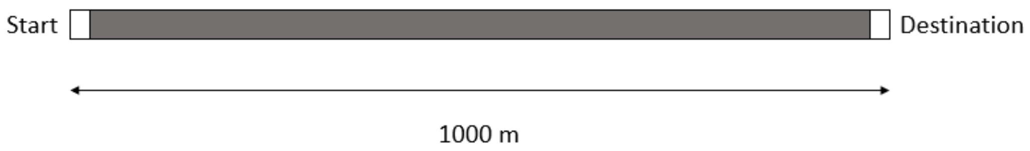
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   The model can include events that occurs during the simulation between the fire spread evolution and evacuation interaction. The integration of traffic flow with fire spread is also implemented through a lane reversal option. The user can define an event which would correspond to a need for lane reversal. This Input can be implemented based on road type (e.g., only larger roads generally use a lane reversal approach). When lane reversal is activated, the capacity of a given road will the automatically change based on various road features (e.g., number of lanes, length of road, etc.).

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   The geometry is a road with a single carriageway and a single lane for a total length of 1000 m. The road type correspond to a speed limit equal to 90 km/h.

3. Scenario configuration

   Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

   One vehicle with an assigned free flow speed corresponding to the speed limit drives to the Destination. After a certain time, an event is triggered that activates the lane reversal function, opening another lane.

4. How have the behaviours been represented?

[x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

[ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

[ ] Blind

[x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

If YES, explain which factors within the configuration were modified and how:

The test was repeated for each of the five vehicle density levels linear from 1 vehicle/km/lane to a vehicle density leading to stopped vehicles on the road segment. The densities used were 1, 19, 38, 56, and 75 vehicles/km/lane.

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.
Vehicles have default settings with no acceleration or deceleration.
The traffic model layer is the only one active during the testing.
The simulation time steps are 1 s.

8. Results

Requested result:

- Times: present this result with an accuracy in the order of seconds and compare it with the expected result (difference should be presented in %).

The simulated result for the different densities is

D1 = 40 s, D2 = 50 s, D3 = 63 s, D4 = 80 s, D5 = 108 s

The expected result for the different densities is

D1 = 40 s, D2 = 50 s, D3 = 63 s, D4 = 81 s, D5 = 108 s

The difference between the results is for D1 = 0 %, D2 = 0 %, D3 = 0 %, D4 = (81-80)/81= 1 %, D5 = 0 %.

Test WT.3. Loss of exit or shelter

Brief description of the test in accordance with the original text and table presented in this document.

Testing that if an exit or a shelter is lost, the route gets re-directed to the other available exit or shelter.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [x] Yes, feature/behaviour explicitly represented

   [ ] Yes, feature/behaviour implicitly represented

   [ ] Partially

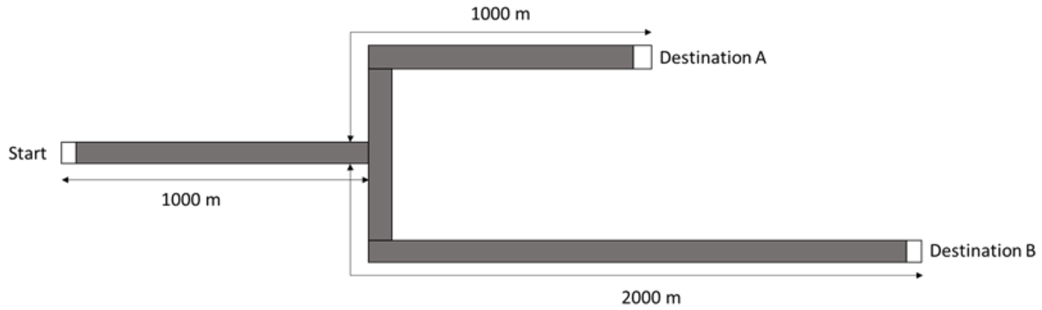
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   Route choice is computed by adopting the open source route planning tool Itinero[4]. The destinations of the cars within the traffic model are user-defined. Destination preferences can be set by the user, or by default, if there are several available destinations, the vehicles select the closest destination as an initial target. The user can also draw areas on the GUI for choosing destinations which override the default nearest option. The model can include events that occurs during the simulation between the fire spread evolution and evacuation interaction.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A road with a single carriageway and a single lane with an intersection leading to two different destinations for a total length of either 1000 m + 1000 m, or 1000 m + 2000 m with a road type corresponding to a speed limit equal to 90 km/h.

3. Scenario configuration

[4] https://www.itinero.tech/

Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

One vehicle with an assigned free flow speed corresponding to the speed limit driving to Destination A. After a certain time, an event is activated that closes the Destination A and forcing the vehicle to change course and take the longer route to Destination B. By default, the vehicle would have taken the shorter since it is both closer and faster.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario.

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

   If YES, explain which factors within the configuration were modified and how:

Describe how you performed the user's actions requested in the test description:

Describing the impact of the loss of exit/shelters on the vehicles that are closely approaching it.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

— Requested result: Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.

The simulated result is the vehicle arriving at Destination B.

The expected result is the vehicle arriving at Destination B.

There is no difference between the results.

Test WT.4. Refuge capacity

Brief description of the test in accordance with the original text and table presented in this document.

Testing that when a refuge reaches it max capacity, vehicles will then drive to the next available refuge.

1. Does the model include a sub-model capable of representing the feature/behaviour included in the test?

   [ ] Yes, feature/behaviour explicitly represented

   [x] Yes, feature/behaviour implicitly represented

   [ ] Partially

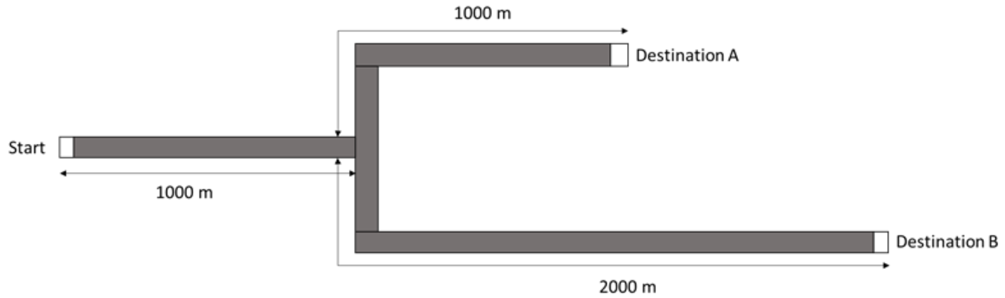
   [ ] No, this feature/behaviour cannot be represented

   If you answered "No", the test report is completed here. If you answer "YES" or "Partially", explain your previous answer and describe the sub-model(s) adopted in your model to represent this feature/behaviour:

   Route choice is computed by adopting the open source route planning tool Itinero. The destinations of the cars within the traffic model are user-defined. Destination preferences can be set by the user, or by default, if there are several available destinations, the vehicles select the closest destination as an initial target. The user can also draw areas on the GUI for choosing destinations which override the default nearest option. The sub-model includes the function that if a shelter reaches max capacity, the shelter becomes unavailable for additional cars that arrives at the shelter.

2. Geometry

   Describe how you represented geometry in your model (figures can be used to show this)



   A road with a single carriageway and a single lane with an intersection leading to two different destinations for a total length of either 1000 m + 1000 m, or 1000 m + 2000 m with a road type corresponding to a Speed limit equal to 90 km/h.

3. Scenario configuration

Describe how you represented the behaviours of people in your model (this should refer to both behaviour and any other factors that affect the performance of the agents)

Two vehicles with an assigned free flow speed corresponding to the speed limit are driving along the road. The vehicles would by default drive towards Destination A since it is both a closer and faster route. Both Destination A and B are refuges with capacity as emergency shelters for one person.

4. How have the behaviours been represented?

   [x] Explicitly: the model has a dedicated option to configure the relevant characteristics and response for this scenario

   [ ] Implicitly: the model does not include a dedicated option to configure all characteristics for this scenario, but it allows the representation of the variable(s) using other model features. If you have selected this option, describe how you implemented this feature(s) in your model.

5. Has the model tester performed a blind or open calculation?

   [ ] Blind

   [x] Open

6. Did you run multiple simulations of the same scenario to produce the results? [YES/NO/NOT REQUIRED] NO

   If YES, how was the variation in results assessed?

7. Did you repeat the test to study different configurations of this test? [YES/NO/NOT REQUIRED] NO

   If YES, explain which factors within the configuration were modified and how:

Describe how you performed the user's actions requested in the test description:

The grid size has default settings of 100 x 100 m and a set of both increased and reduced cell sizes.

The traffic model layer is the only one active during the testing.

The simulation time steps are 1 s.

8. Results

— Requested result: Chosen routes/exit(s): present which route(s)/exit(s) has been chosen by people in the simulations and compare it with the expected result.

The simulated result is one vehicle arrives at Destination A and one vehicle arrives at Destination B.

The expected result is one vehicle arrives at Destination A and one vehicle arrives at Destination B.

There is no difference between the results.

Annex C
Extracted PeMS plots

Total of 80000 people from zones 1-5 and 7 are ordered to evacuate.

Total of 180000 people from zones 1-10 are ordered to evacuate.

Nothing out of the ordinary to challenge the road capacity. Seems like ordinary occupancy, flow and speed. The flow could be noteworthy of around 3000 Veh/Hour.

Is this because this location is far away enough from the large city congestions for the traffic to stabilize?

Total of 80000 people from zones 1-5 and 7 are ordered to evacuate.

Total of 180000 people from zones 1-10 are ordered to evacuate.

Total of 3000 people from zones 1-3 and 5 are still ordered to evacuate.

No longer any evacuation order in place.

Total of 3000 people from zones 1-3 and 5 are still ordered to evacuate.

No longer any evacuation order in place.

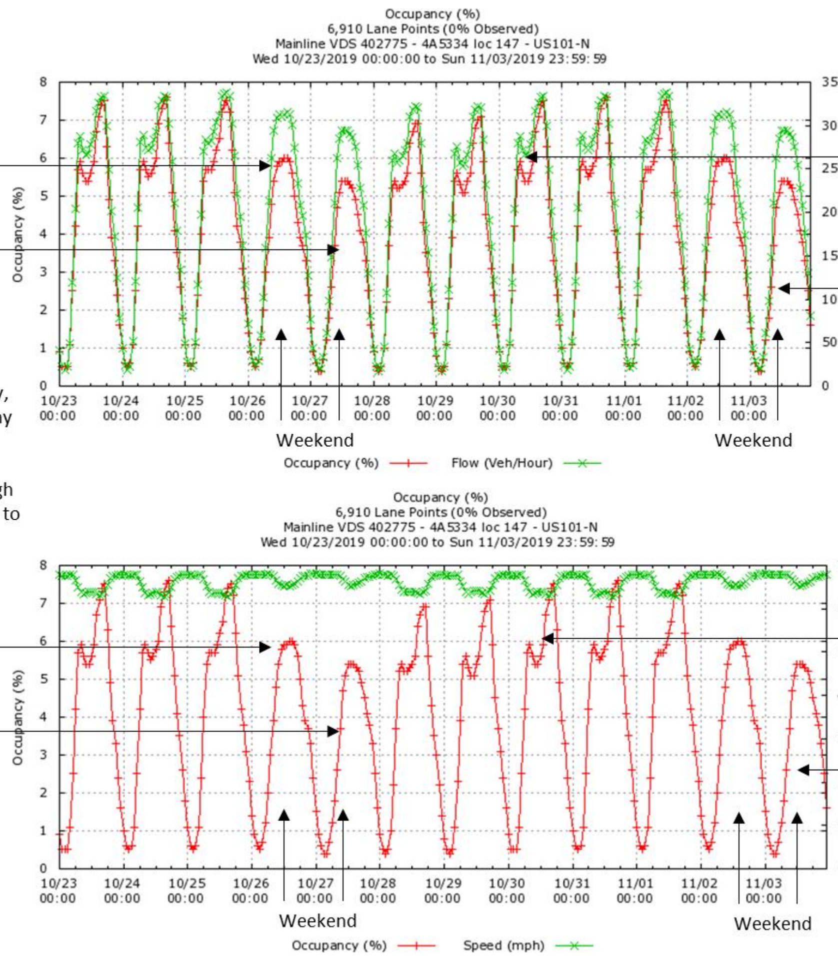


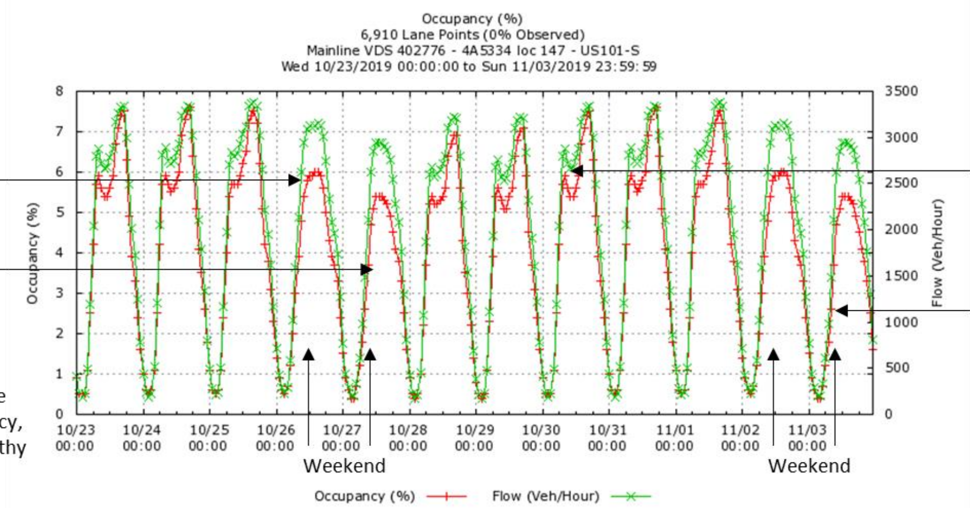
Figure 18 – Occupancy, flow and speed observed at 4A5334 loc 147 US101-N after fire ignition, taken from the PeMS database.

Total of 80000 people from zones 1-5 and 7 are ordered to evacuate.

Total of 180000 people from zones 1-10 are ordered to evacuate.

Nothing out of the ordinary to challenge the road capacity. Seems like ordinary occupancy, flow and speed. The flow could be noteworthy of around 3000 Veh/Hour.

Is this because this location is far away enough from the large city congestions for the traffic to stabilize?

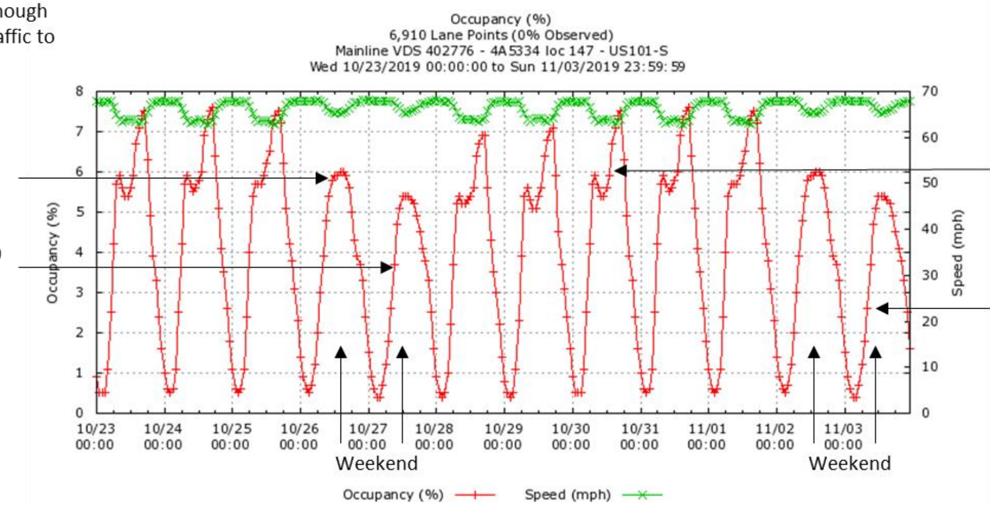


Total of 3000 people from zones 1-3 and 5 are still ordered to evacuate.

No longer any evacuation order in place.

Total of 80000 people from zones 1-5 and 7 are ordered to evacuate.

Total of 180000 people from zones 1-10 are ordered to evacuate.



Total of 3000 people from zones 1-3 and 5 are still ordered to evacuate.

No longer any evacuation order in place.

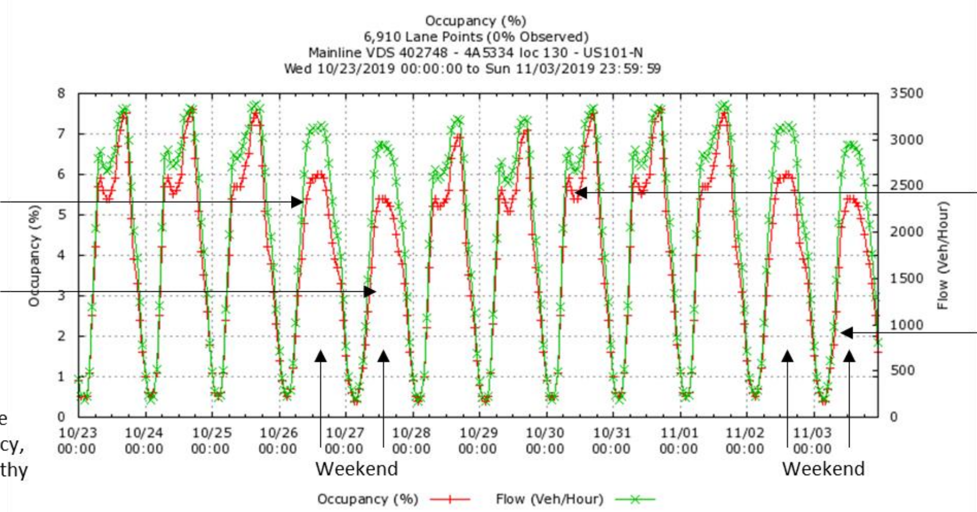
Figure 19 - Occupancy, flow and speed observed at 4A5334 loc 147 US101-S after fire ignition, taken from the PeMS database.

Total of 80000 people from zones 1-5 and 7 are ordered to evacuate.

Total of 180000 people from zones 1-10 are ordered to evacuate.

Total of 3000 people from zones 1-3 and 5 are still ordered to evacuate.

No longer any evacuation order in place.



Nothing out of the ordinary to challenge the road capacity. Seems like ordinary occupancy, flow and speed. The flow could be noteworthy of around 3000 Veh/Hour.

Is this because this location is far away enough from the large city congestions for the traffic to stabilize?

Total of 80000 people from zones 1-5 and 7 are ordered to evacuate.

Total of 180000 people from zones 1-10 are ordered to evacuate.

Total of 3000 people from zones 1-3 and 5 are still ordered to evacuate.

No longer any evacuation order in place.

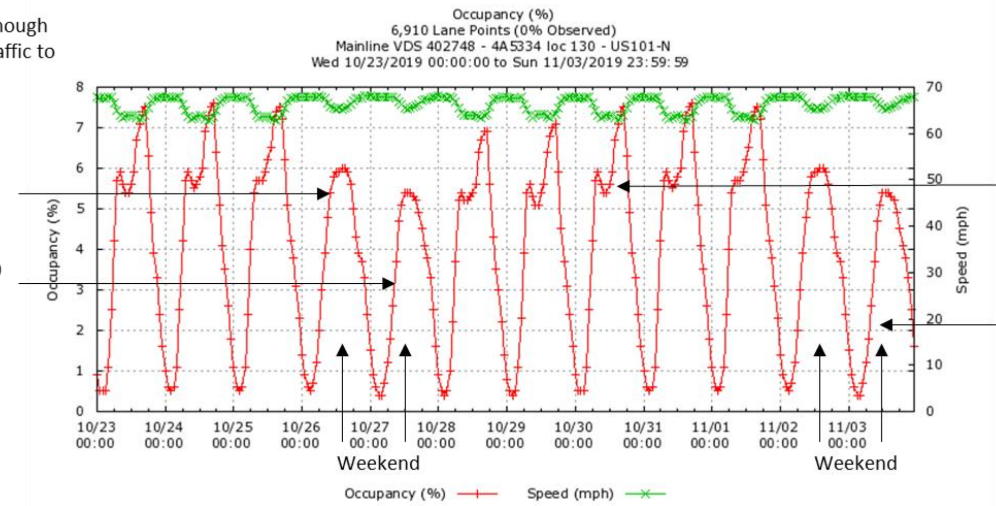


Figure 20 - Occupancy, flow and speed observed at 4A5334 loc 130 US101-N after fire ignition, taken from the PeMS database.

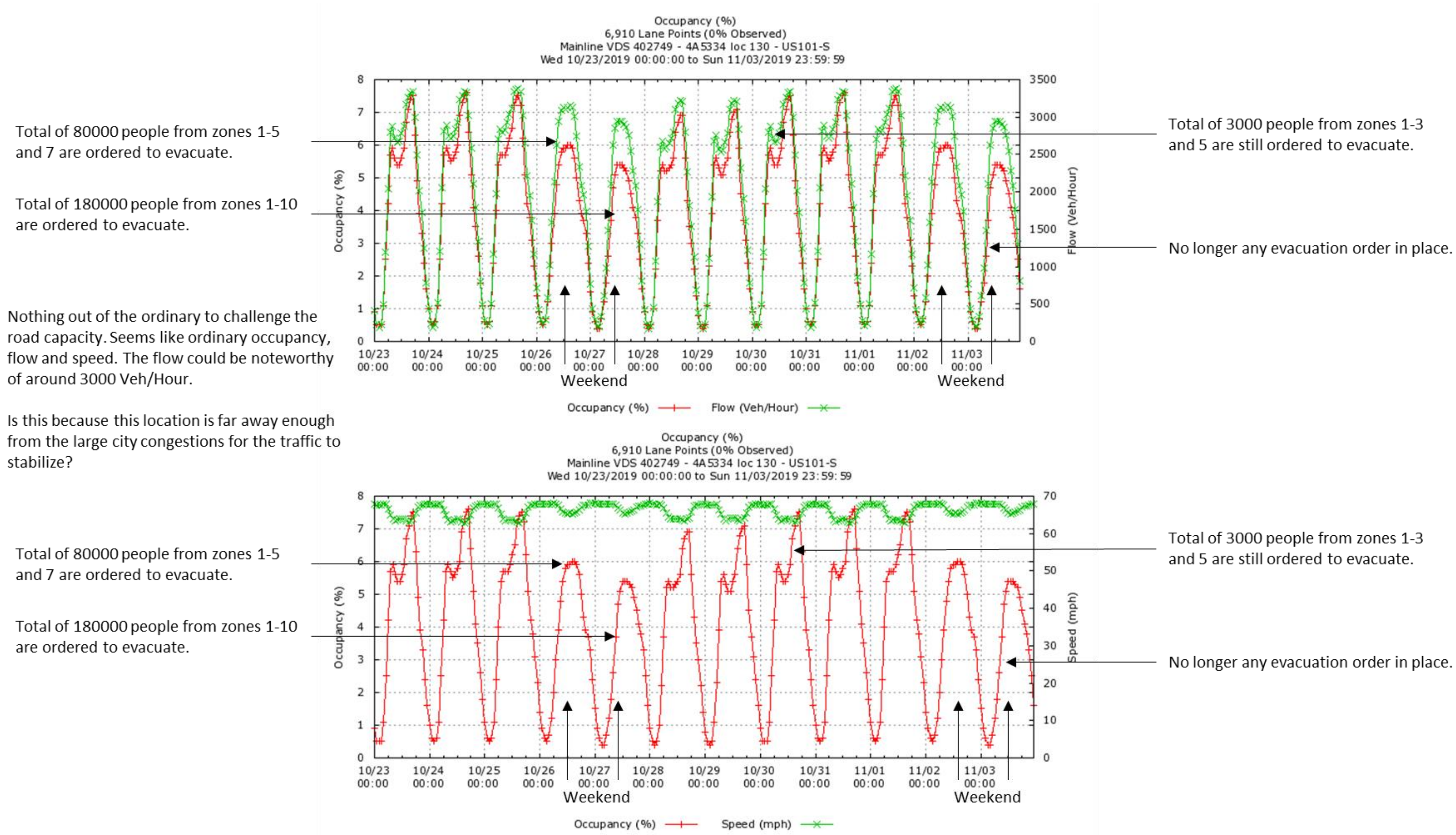


Figure 21 - Occupancy, flow and speed observed at 4A5334 loc 130 US101-S after fire ignition, taken from the PeMS database.

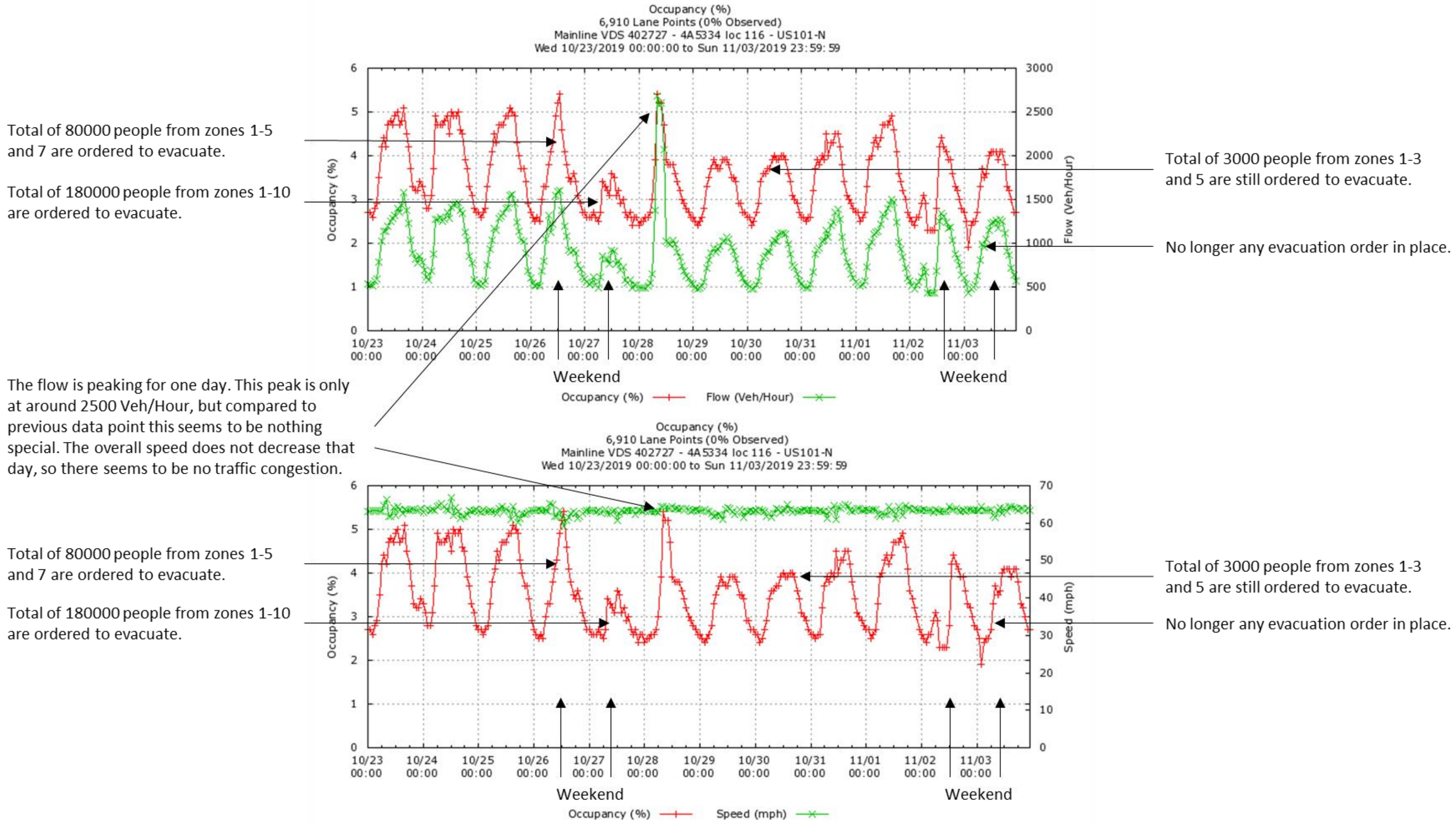


Figure 22 - Occupancy, flow and speed observed at 4A5334 loc 116 US101-N after fire ignition, taken from the PeMS database.

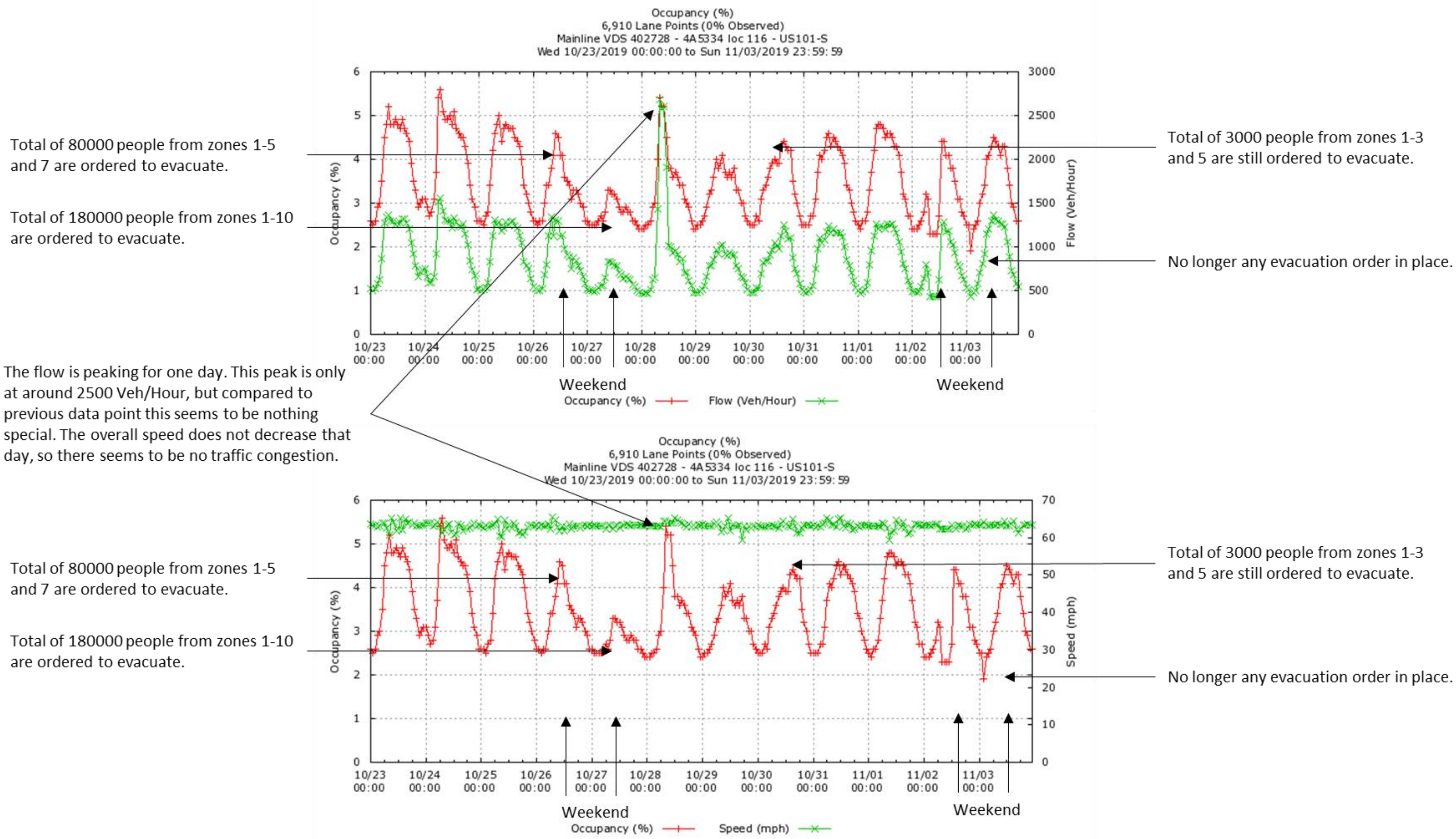


Figure 23 - Occupancy, flow and speed observed at 4A5334 loc 116 US101-S after fire ignition, taken from the PeMS database.

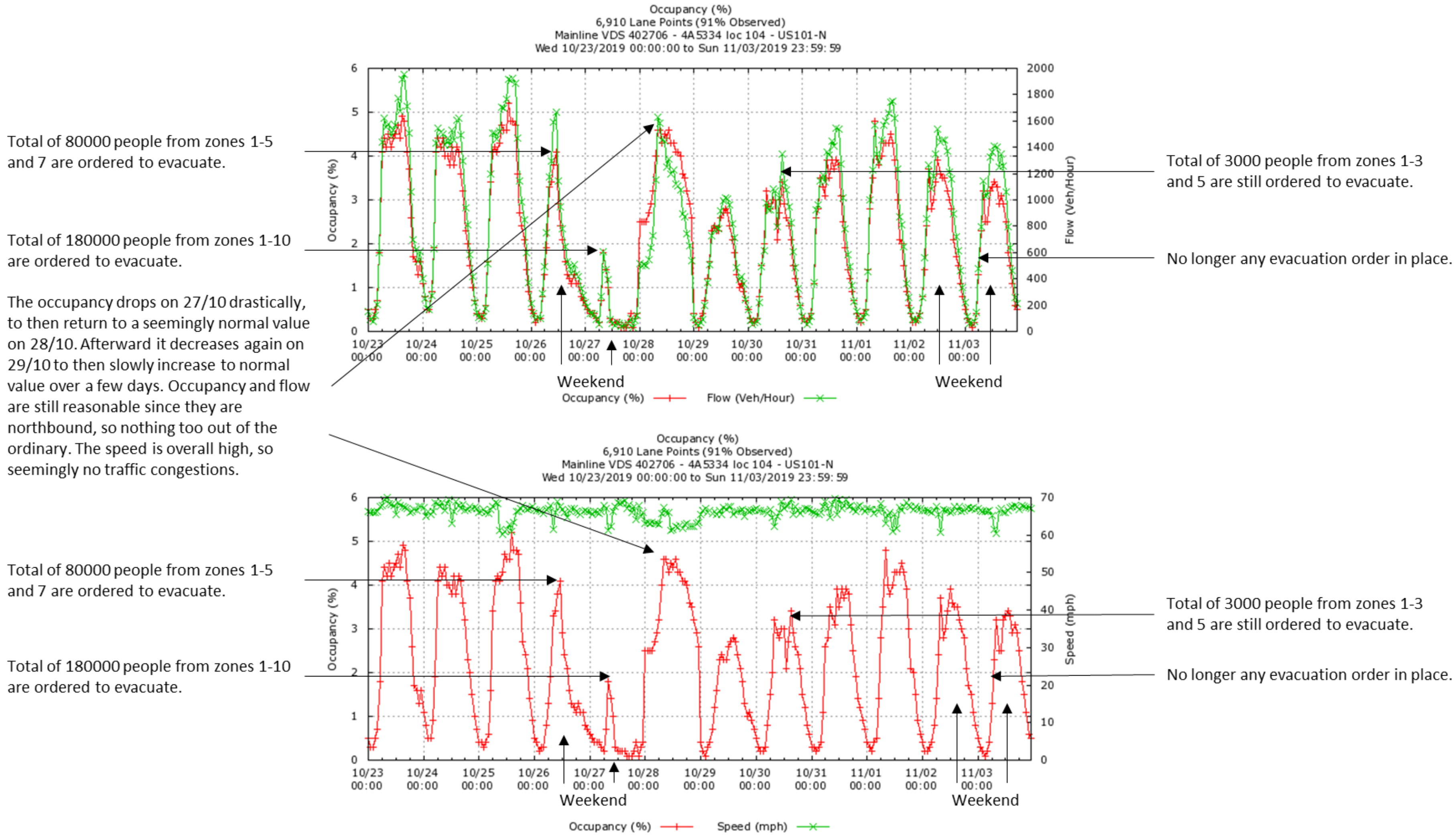


Figure 24 - Occupancy, flow and speed observed at 4A5334 loc 104 US101-N after fire ignition, taken from the PeMS database.

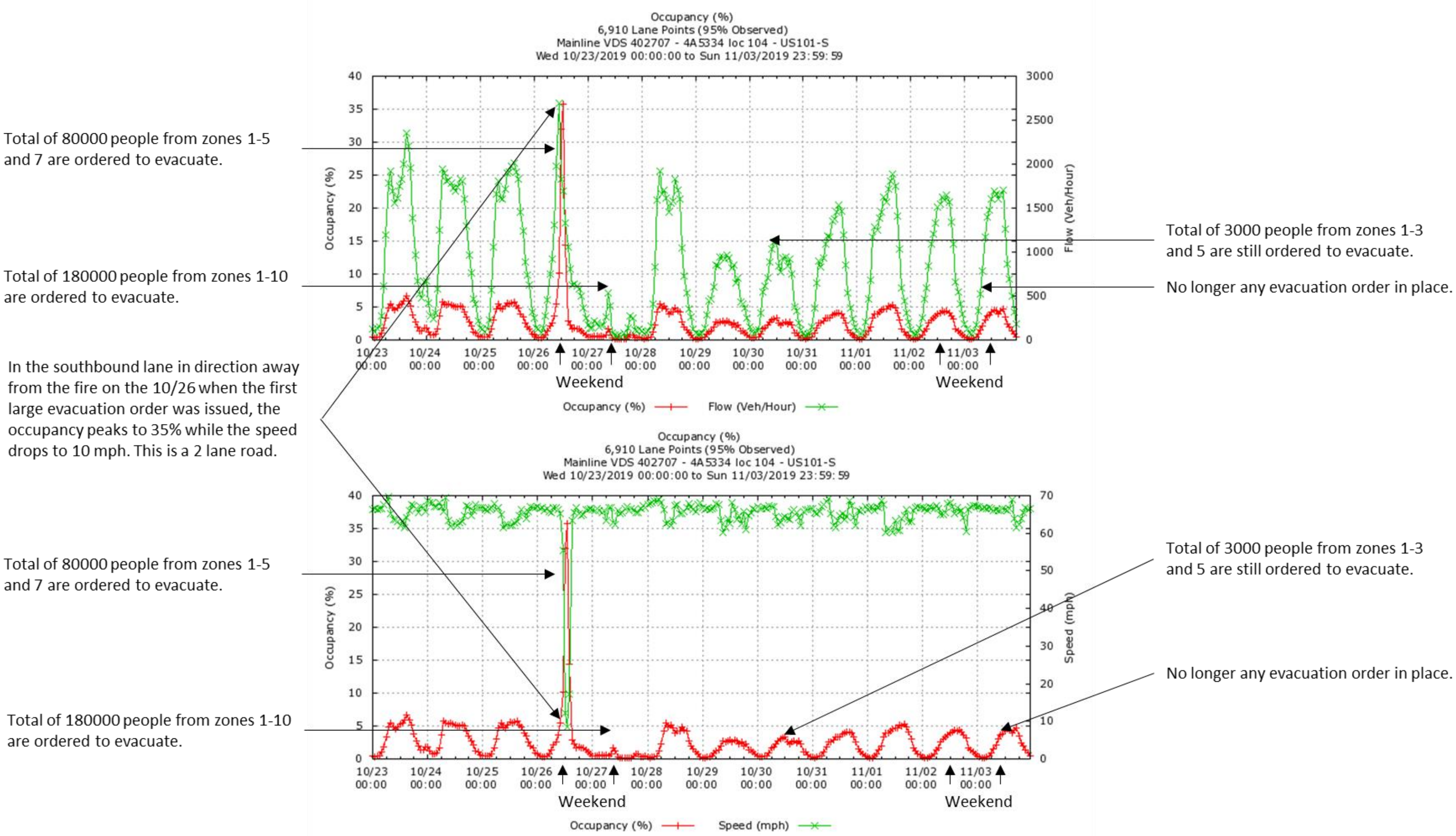


Figure 25 - Occupancy, flow and speed observed at 4A5334 loc 104 US101-S after fire ignition, taken from the PeMS database.

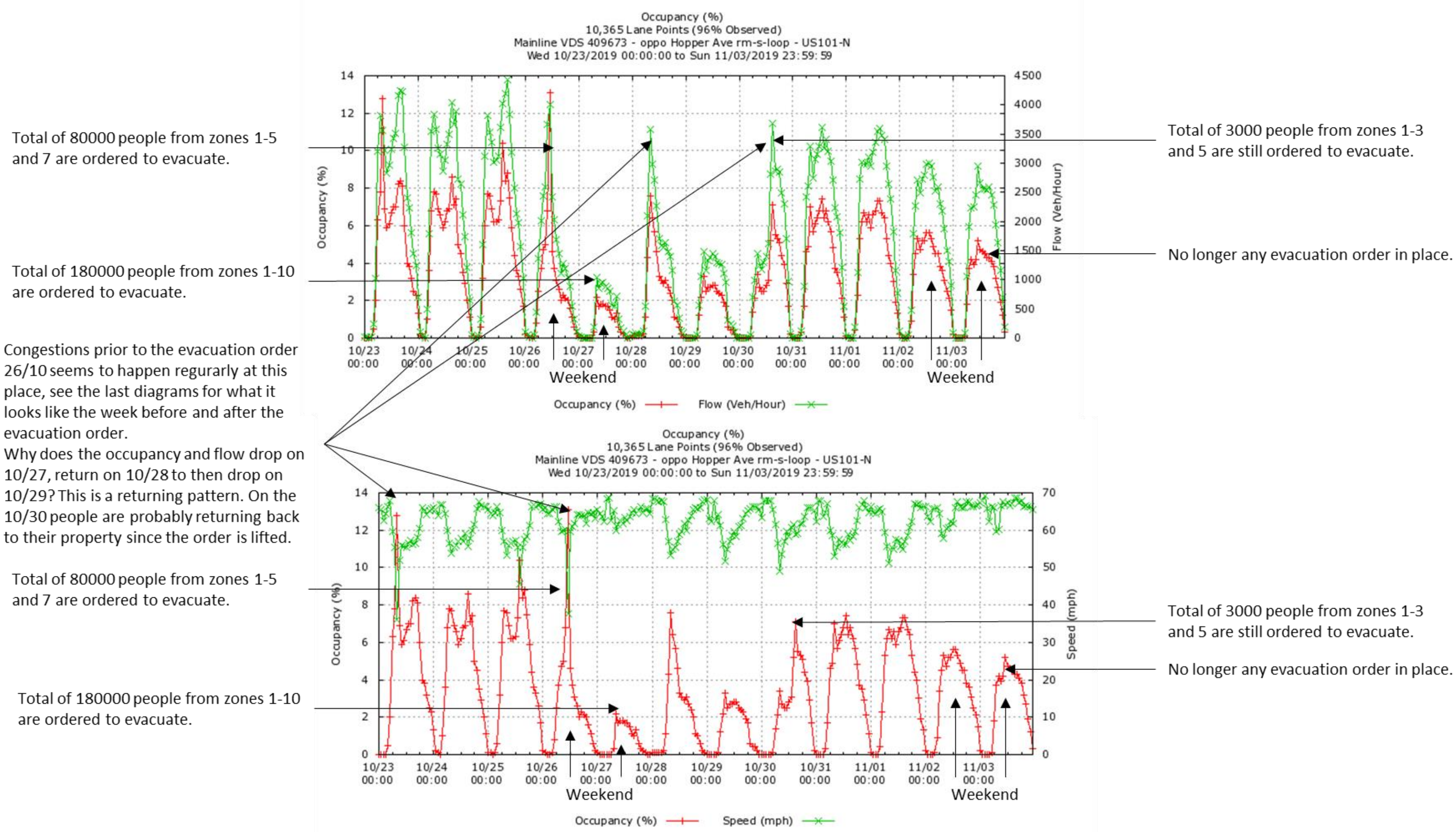


Figure 26 - Occupancy, flow and speed observed at oppo Hopper Ave rm-s-loop US101-N after fire ignition, taken from the PeMS database.

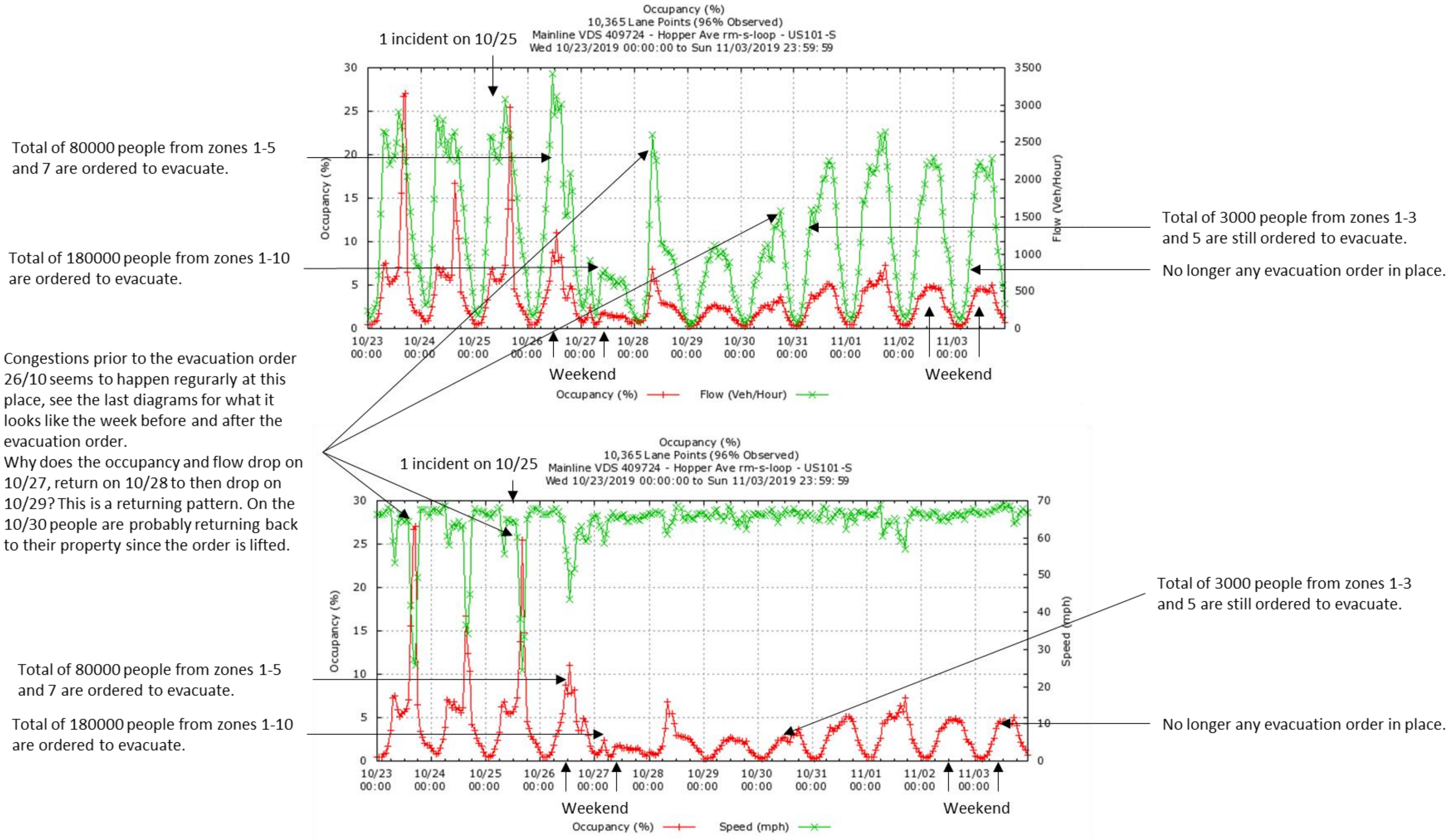


Figure 27 - Occupancy, flow and speed observed at Hopper Ave rm-s-loop US101-S after fire ignition, taken from the PeMS database.

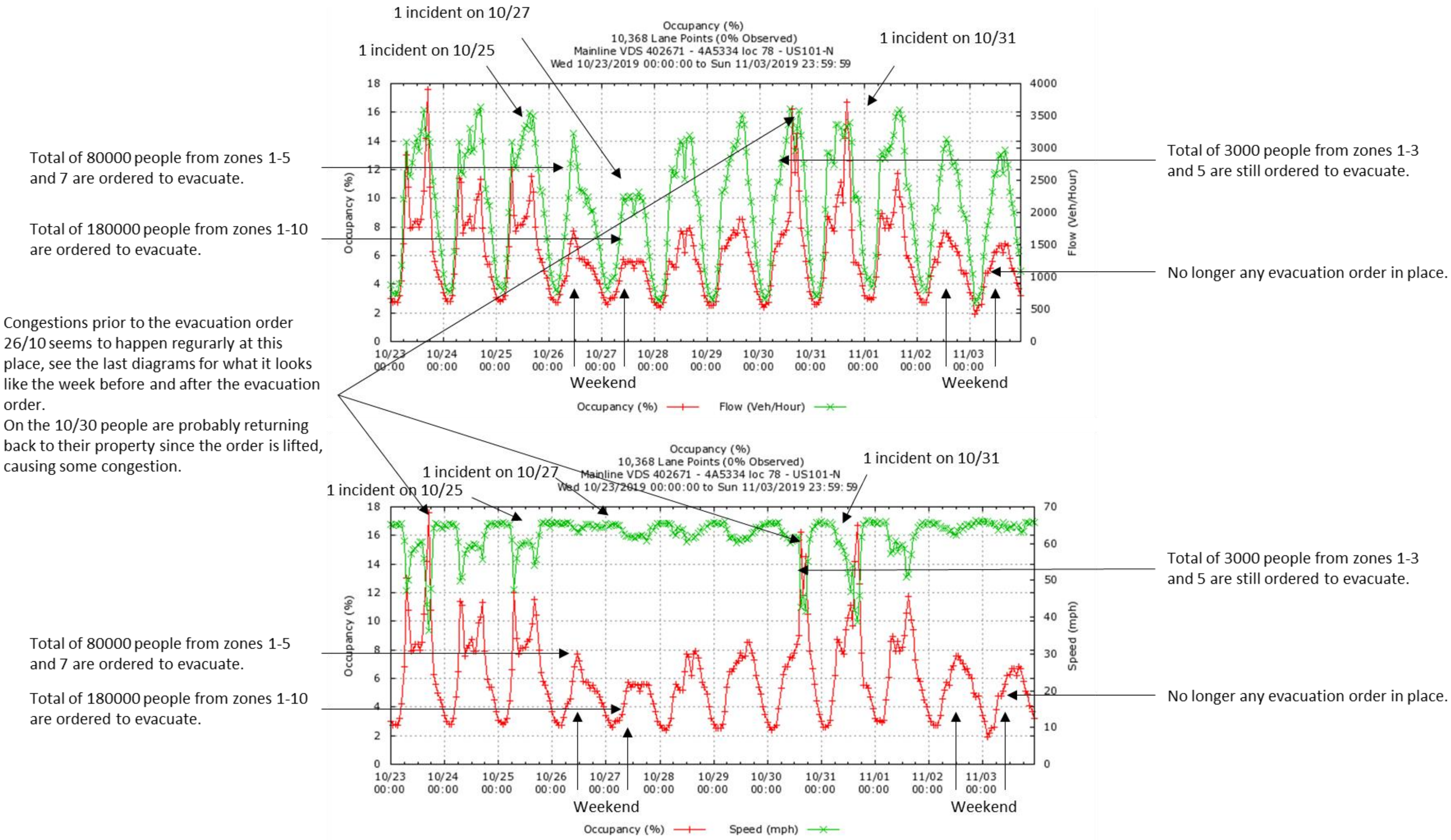


Figure 28 - Occupancy, flow and speed observed at 4A5334 loc 78 US101-N after fire ignition, taken from the PeMS database.

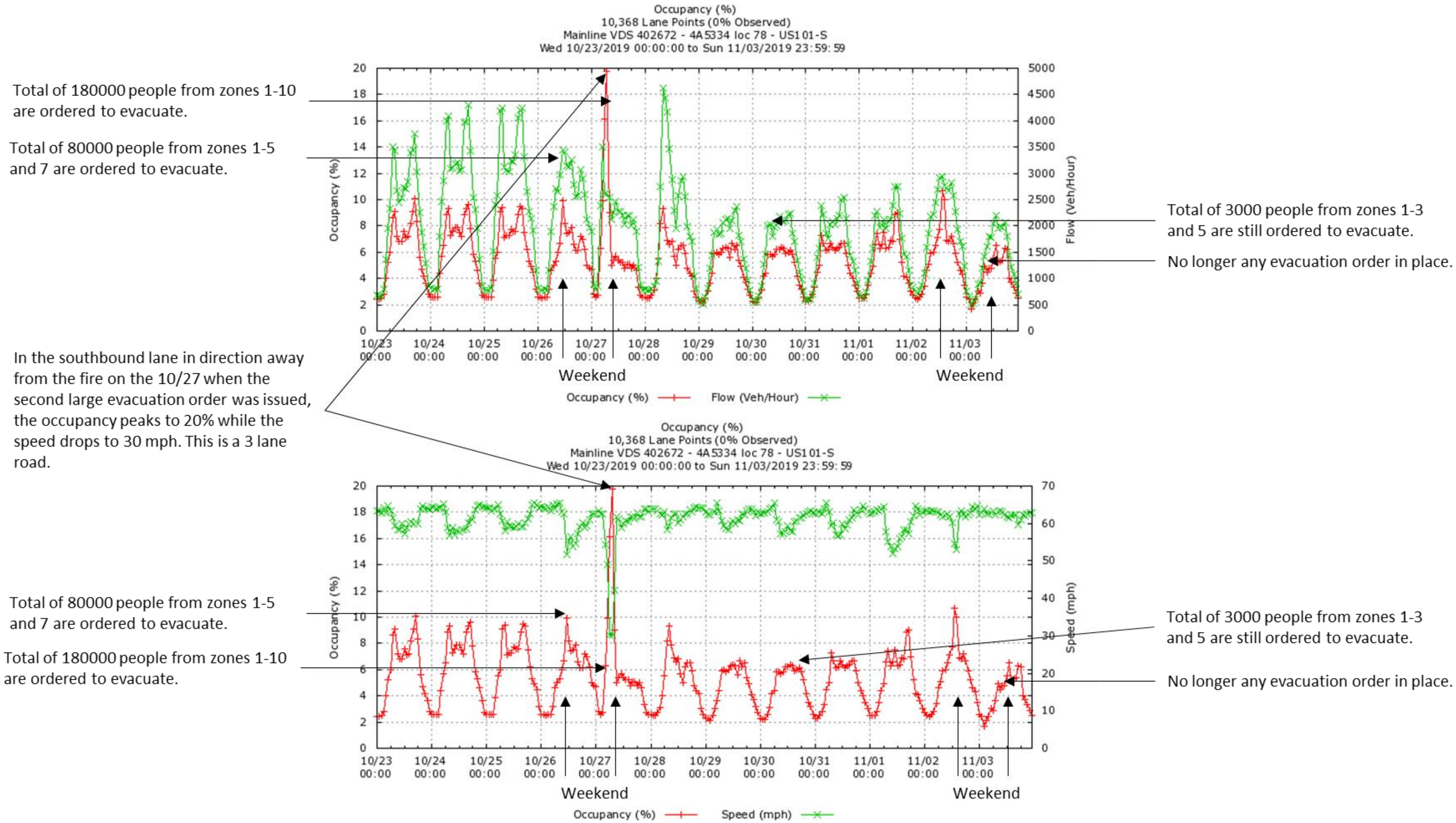


Figure 29 - Occupancy, flow and speed observed at 4A5334 loc 78 US101-S after fire ignition, taken from the PeMS database.

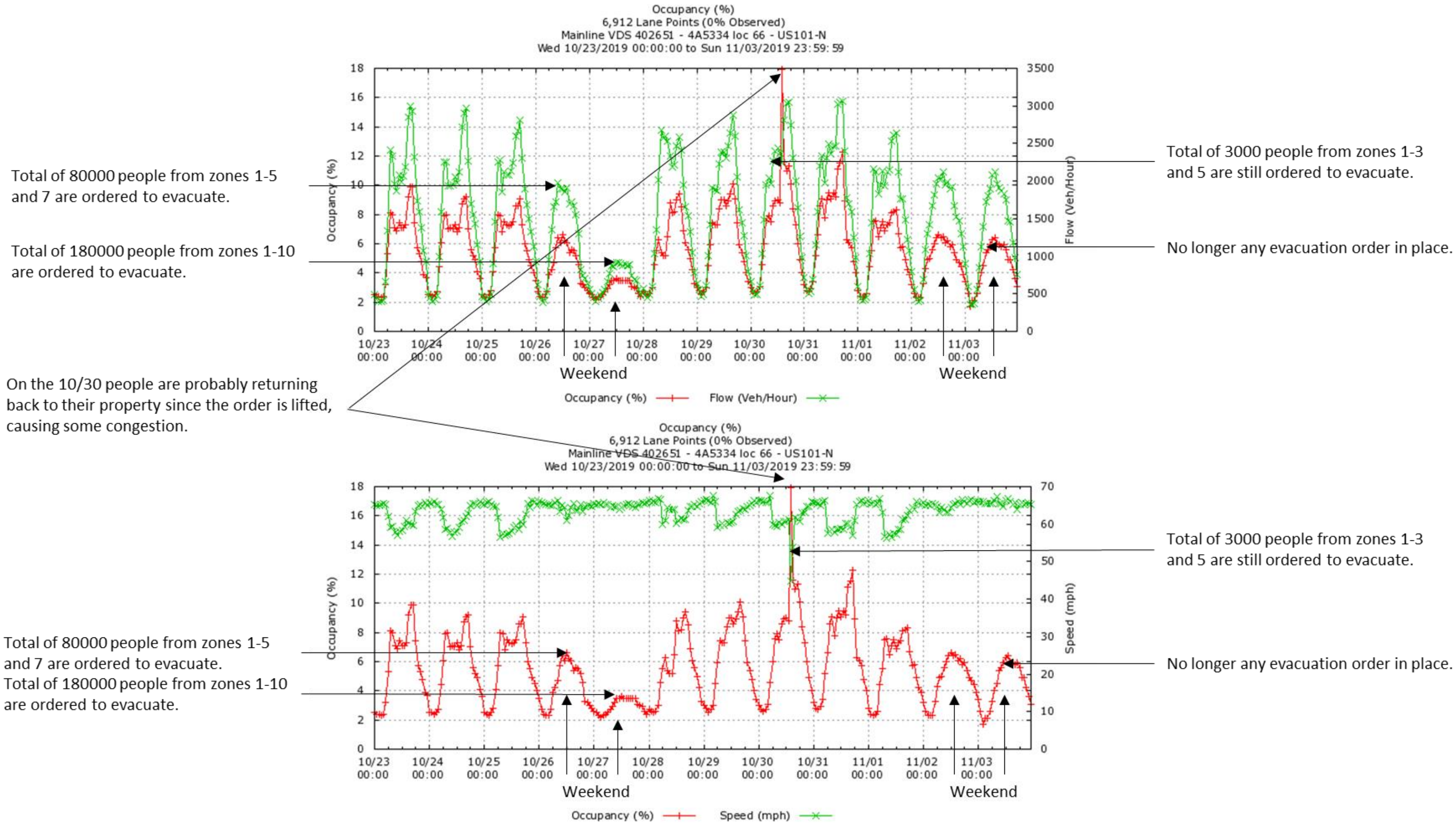


Figure 30 - Occupancy, flow and speed observed at 4A5334 loc 66 US101-N after fire ignition, taken from the PeMS database.

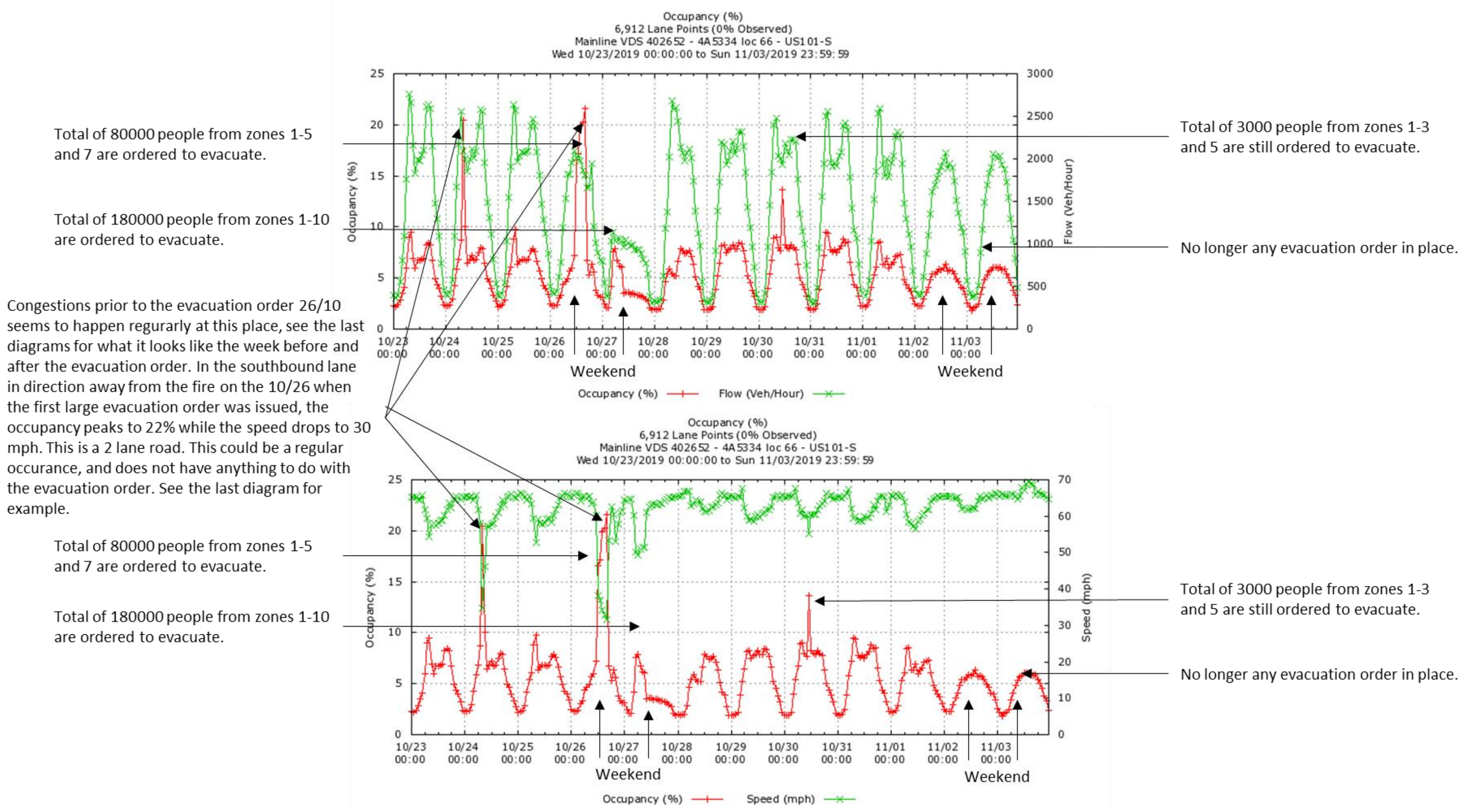


Figure 31 - Occupancy, flow and speed observed at 4A5334 loc 66 US101-S after fire ignition, taken from the PeMS database.

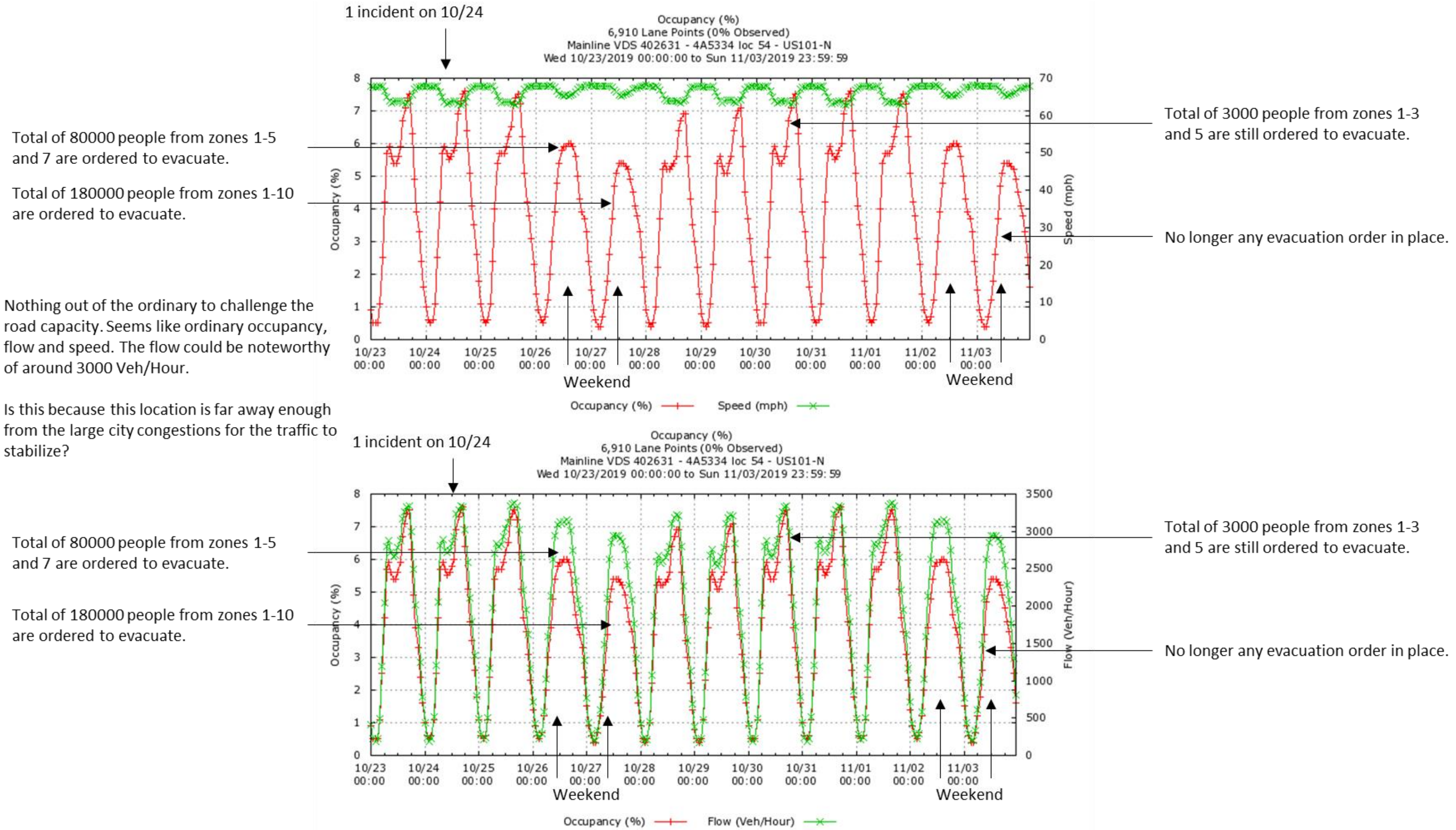


Figure 32 - Occupancy, flow and speed observed at 4A5334 loc 54 US101-N after fire ignition, taken from the PeMS database.

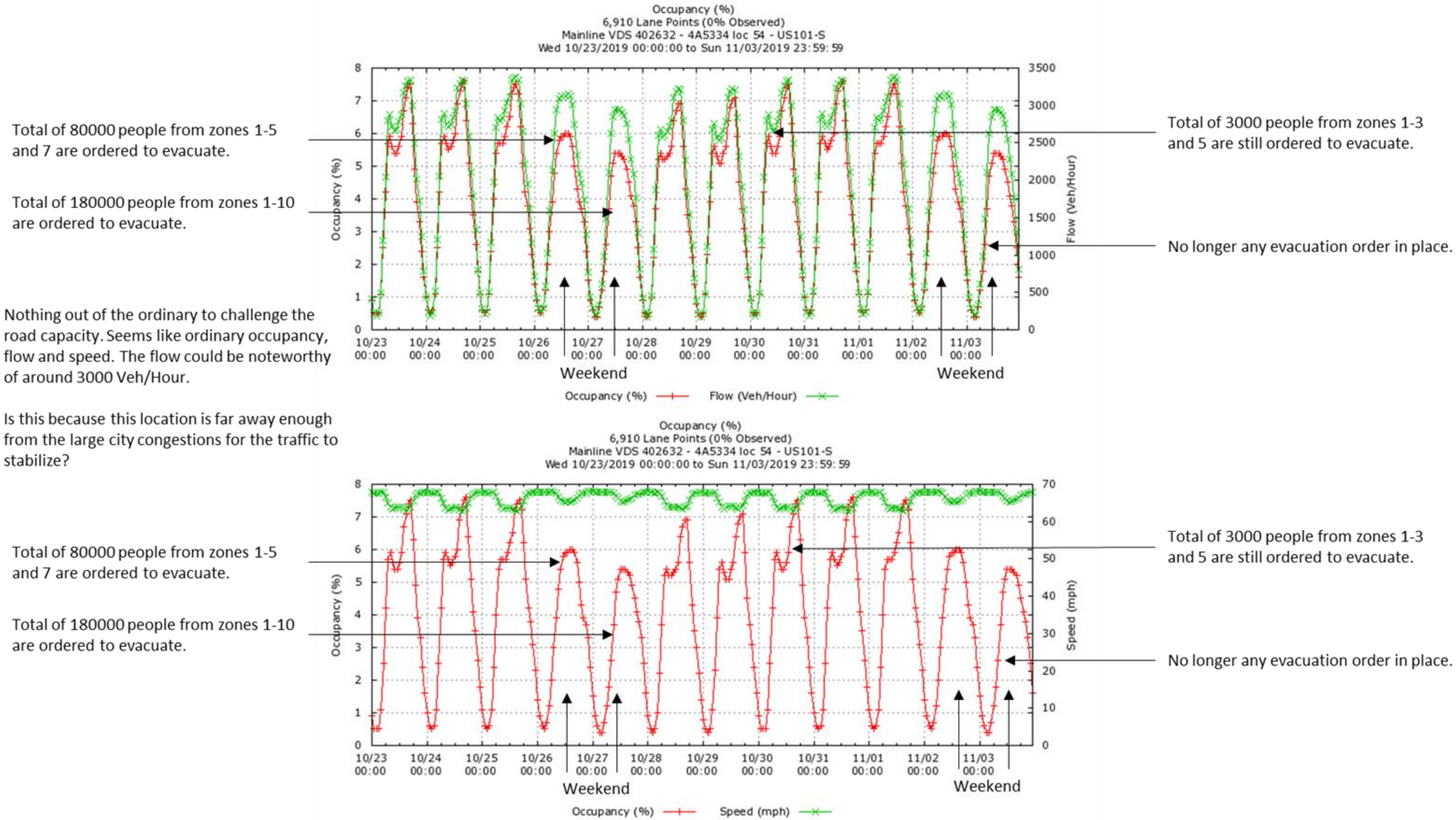


Figure 33 - Occupancy, flow and speed observed at 4A5334 loc 54 US101-S after fire ignition, taken from the PeMS database.

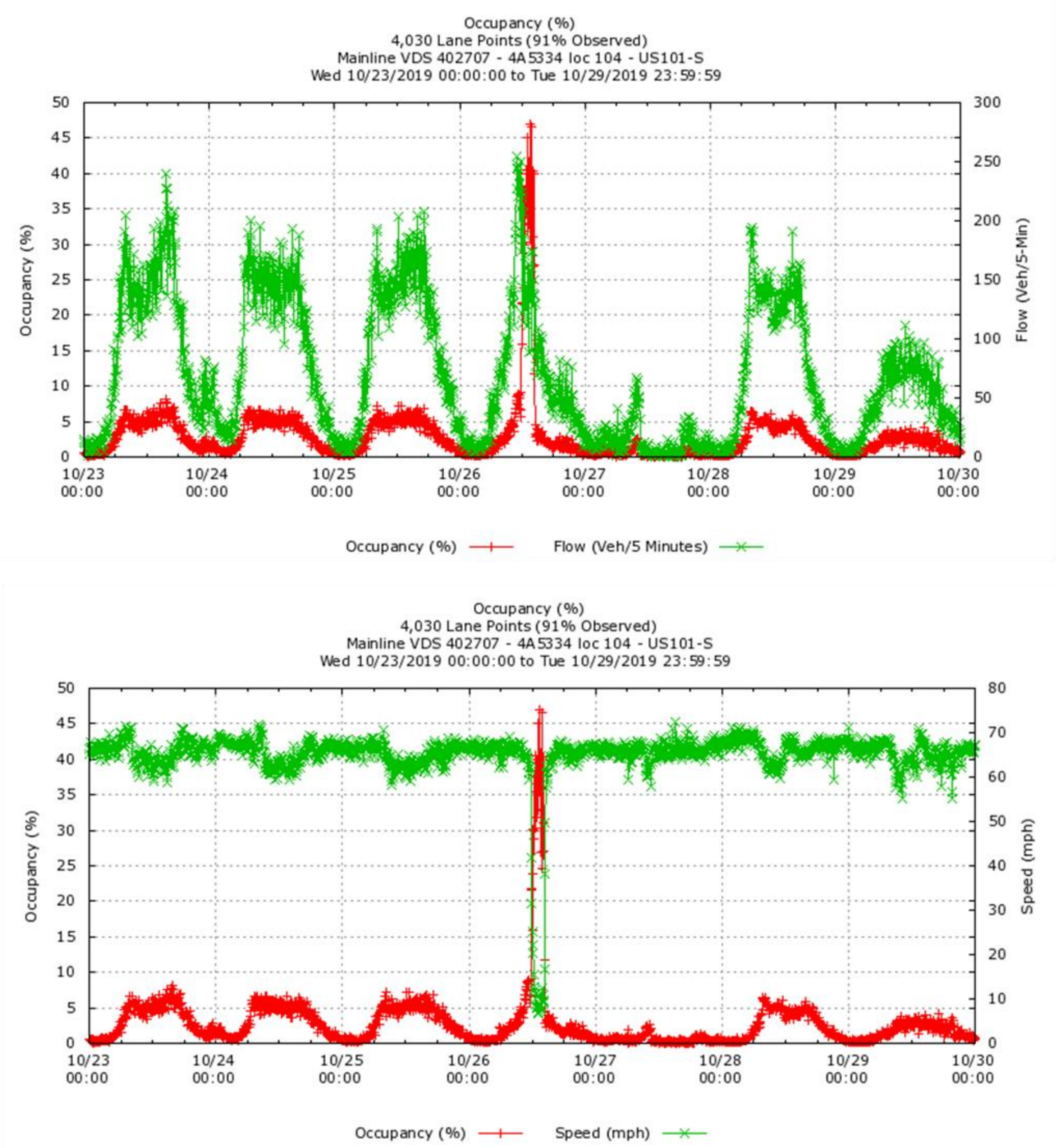
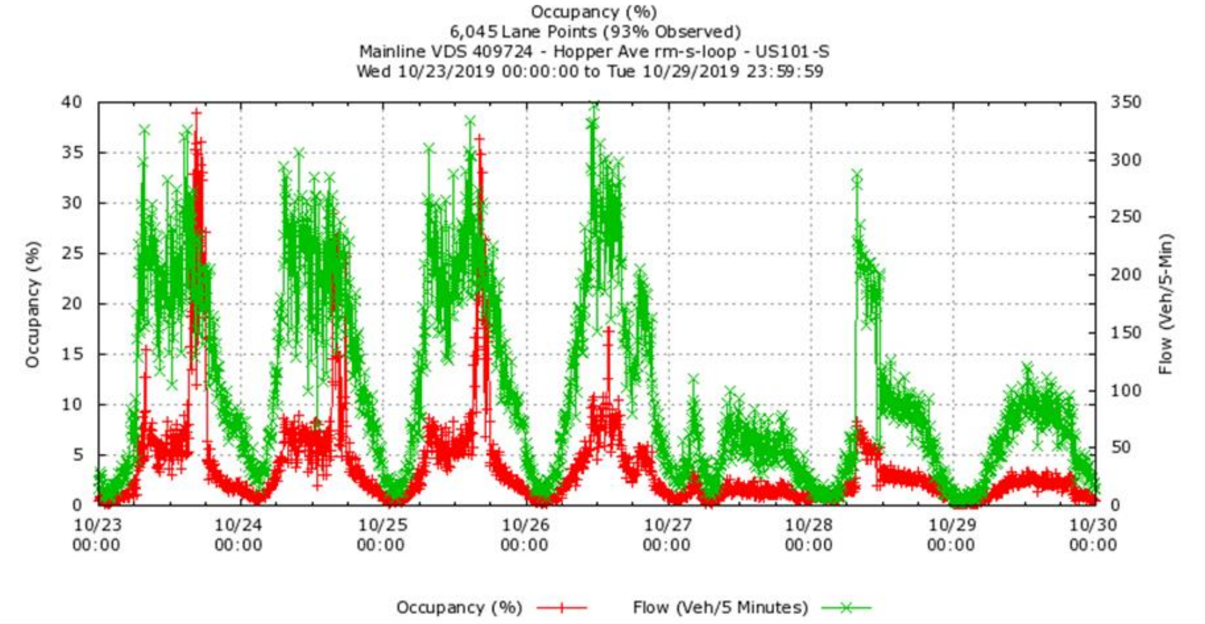


Figure 34 - Occupancy, flow and speed observed at 4A5334 loc 104 US101-S after fire ignition, taken from the PeMS database.



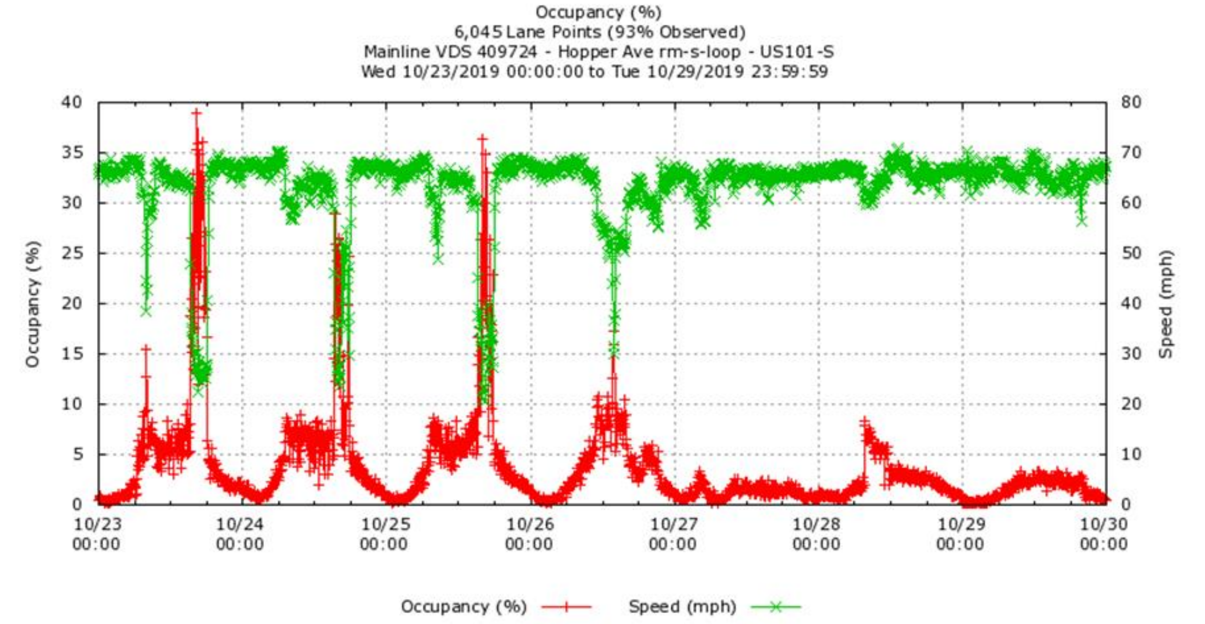


Figure 35 - Occupancy, flow and speed observed at Hopper Ave rm-s-loop US101-S after fire ignition, taken from the PeMS database.

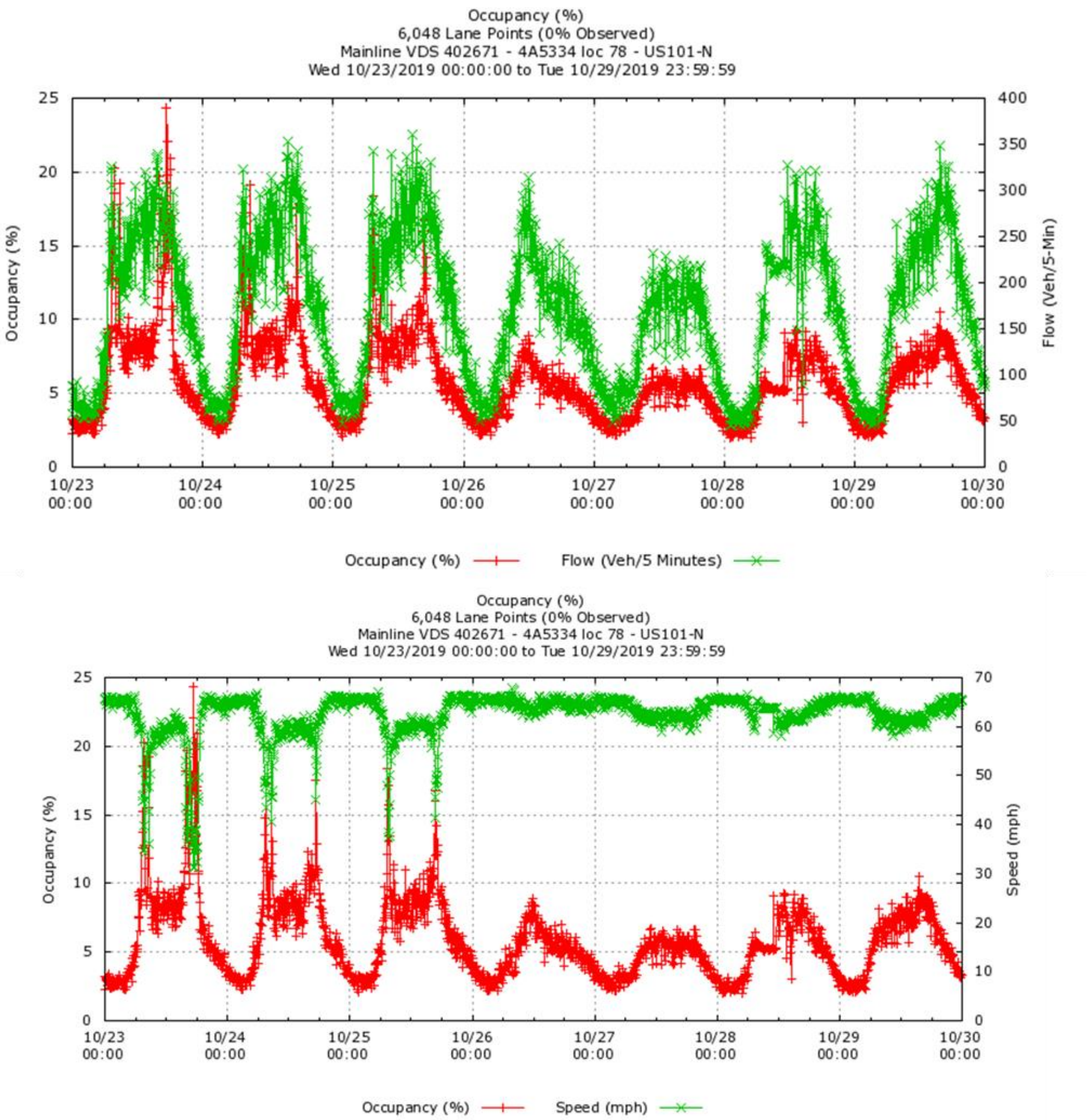


Figure 36 - Occupancy, flow and speed observed at 4A5334 loc 78 US101-N after fire ignition, taken from the PeMS database.

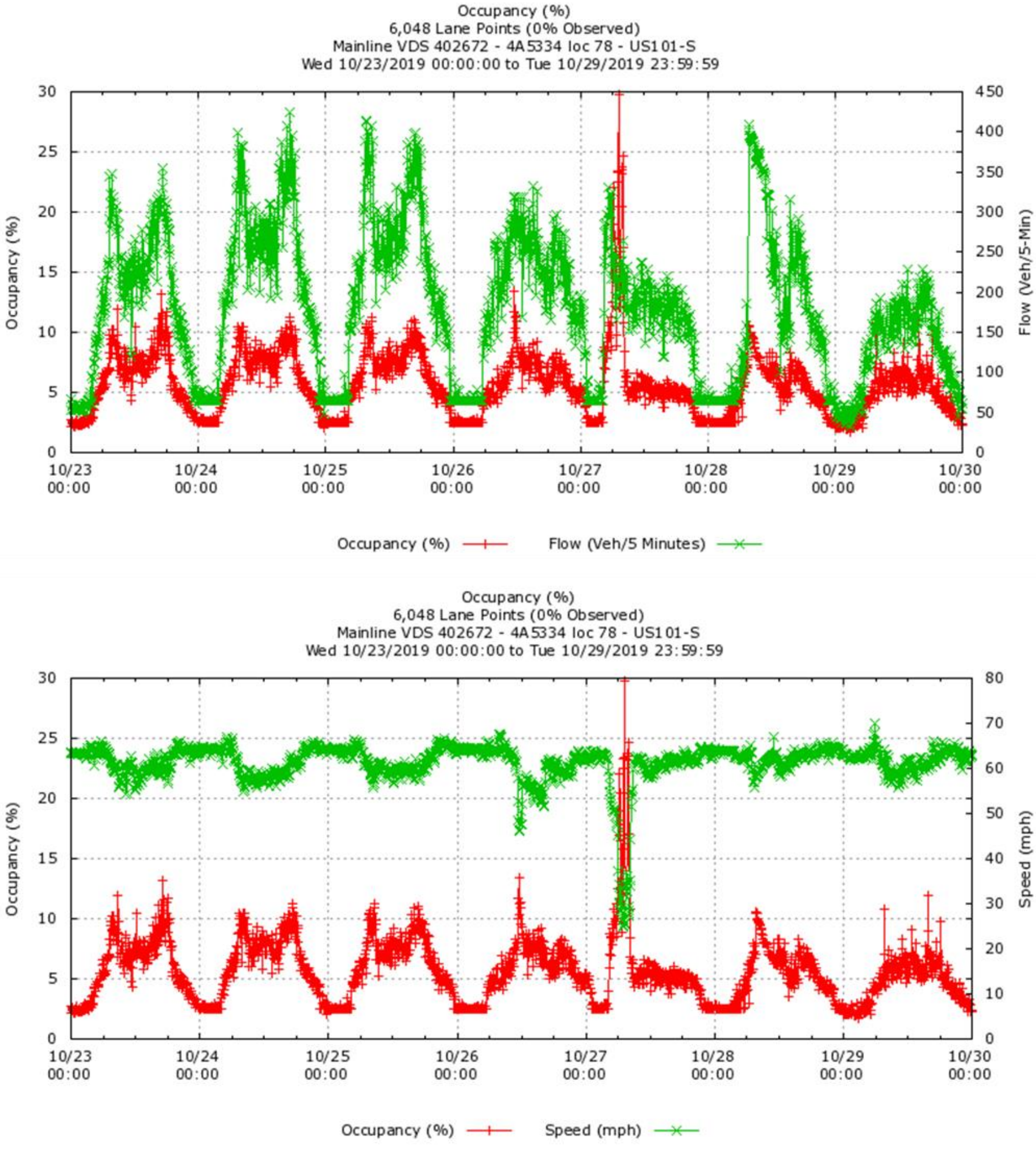
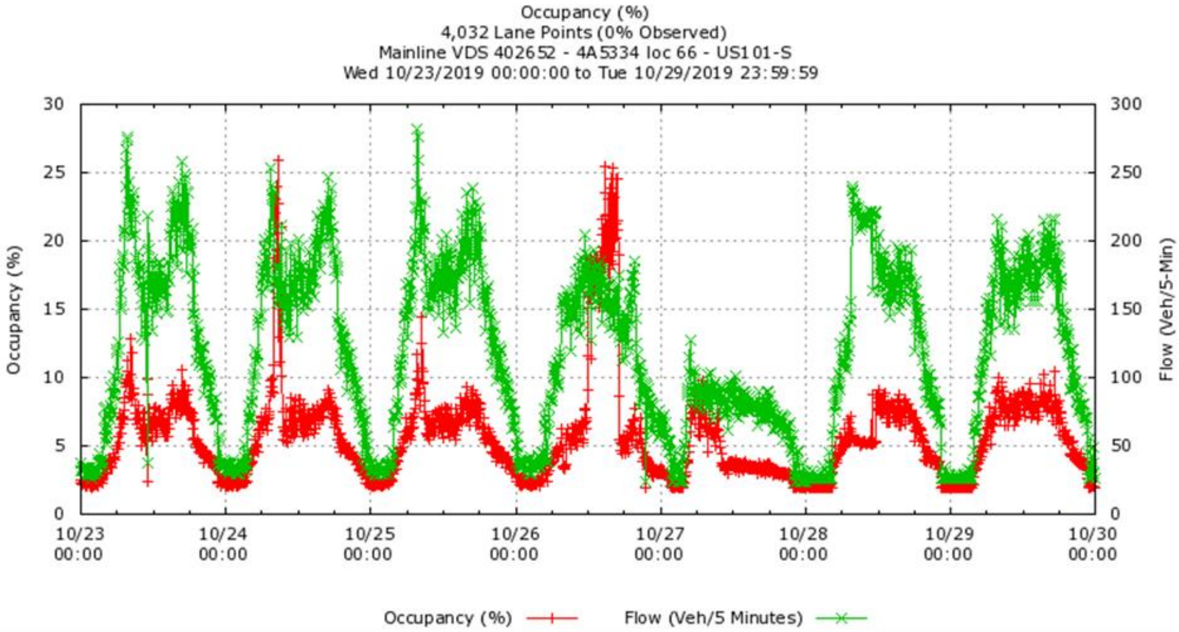


Figure 37 - Occupancy, flow and speed observed at 4A5334 loc 78 US101-S after fire ignition, taken from the PeMS database.



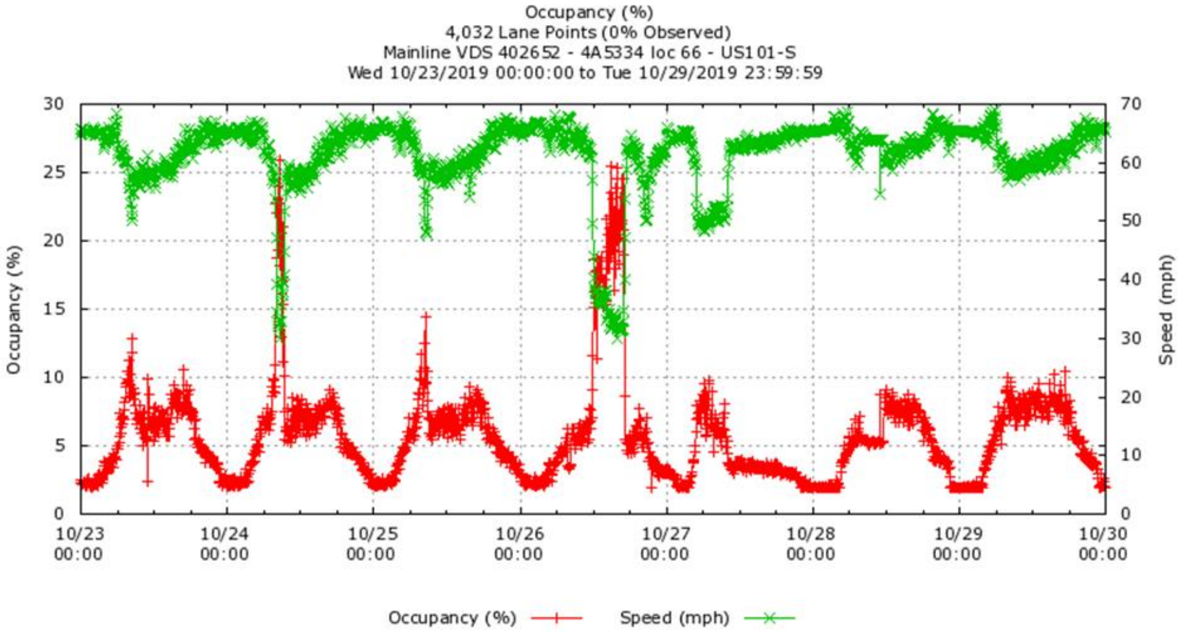


Figure 38 - Occupancy, flow and speed observed at 4A5334 loc 66 US101-S after fire ignition, taken from the PeMS database.

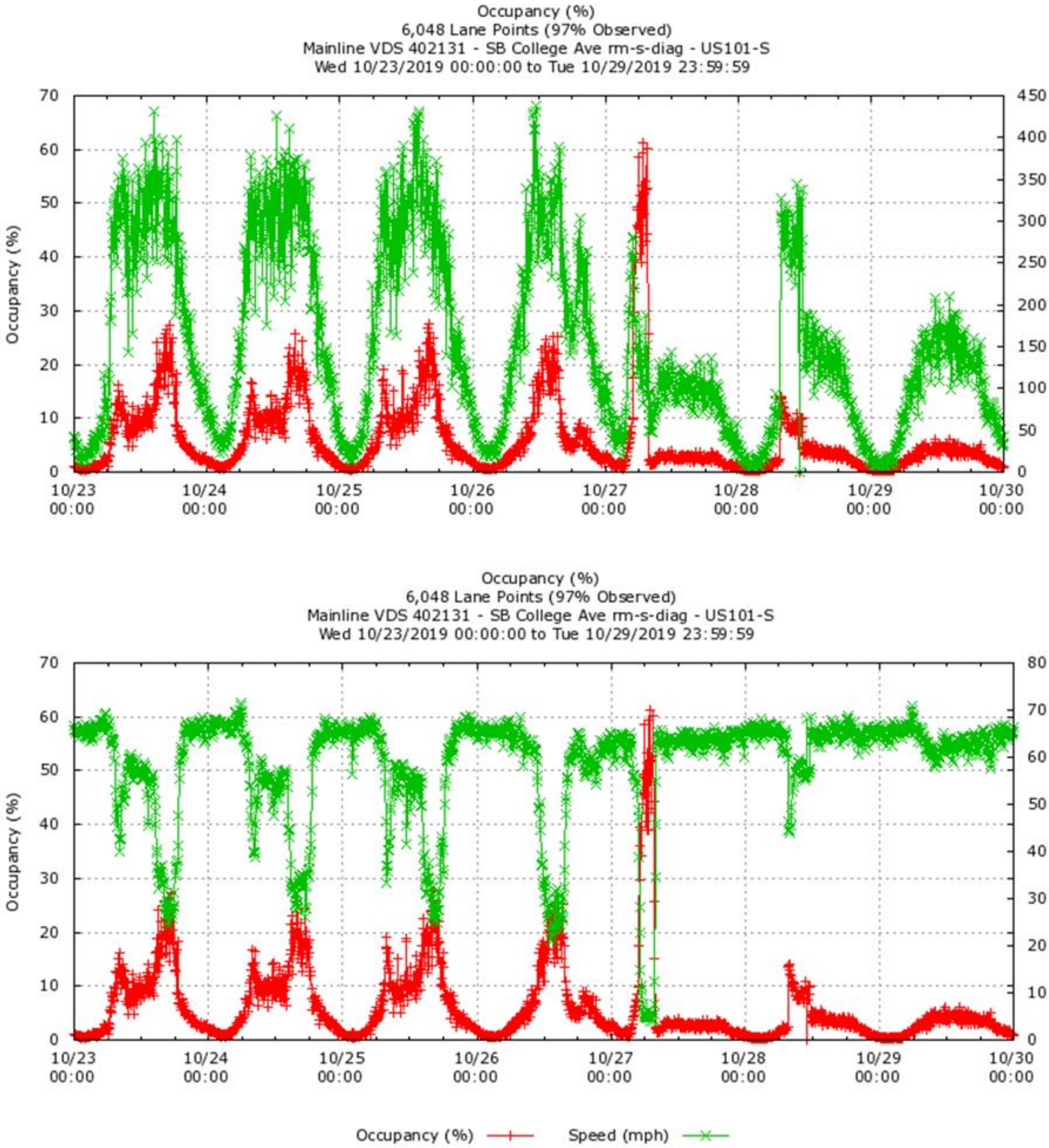
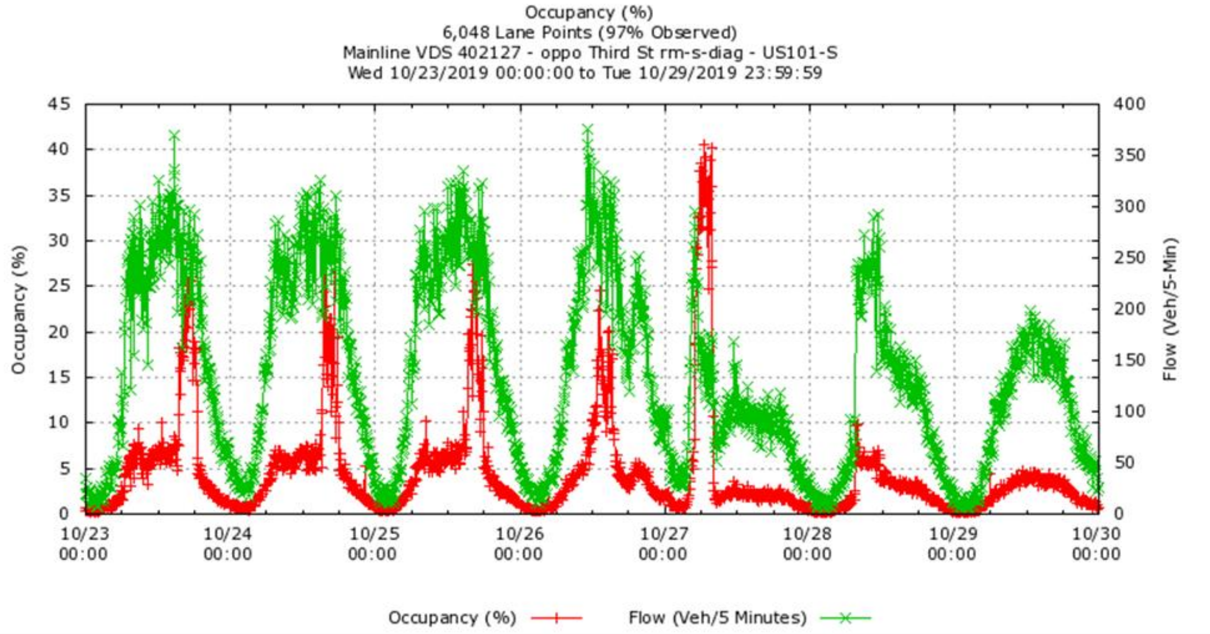


Figure 39 - Occupancy, flow and speed observed at SB College Ave rm-s-diag US101-S after fire ignition, taken from the PeMS database.



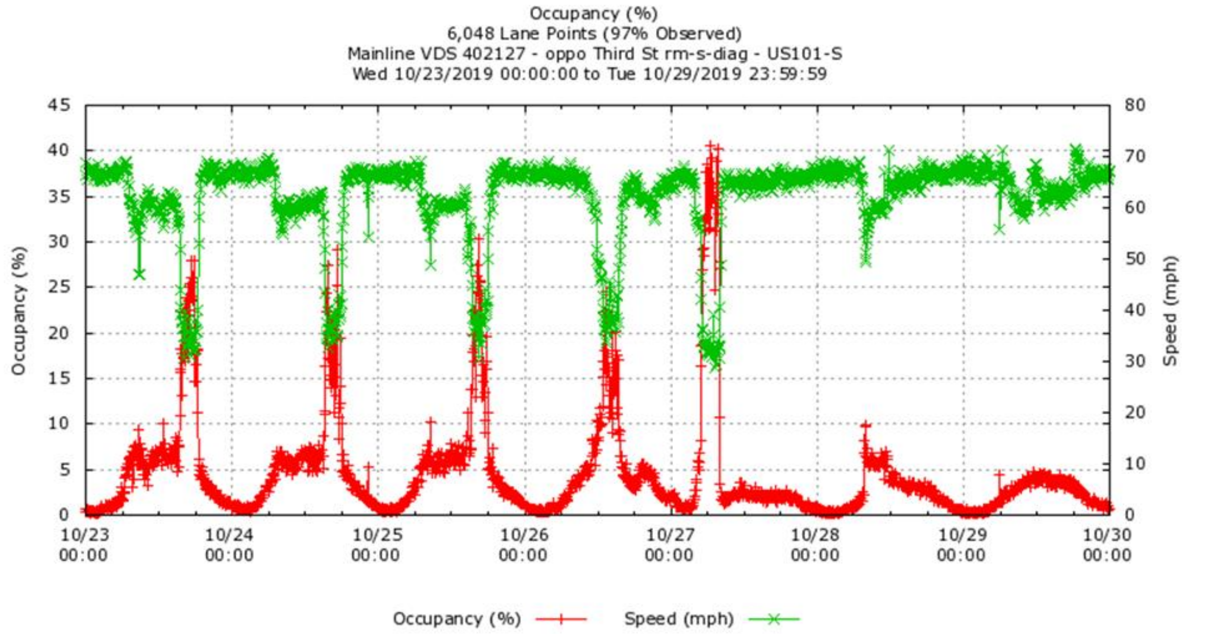


Figure 40 - Occupancy, flow and speed observed at oppo Third St rm-s-diag US101-S after fire ignition, taken from the PeMS database.

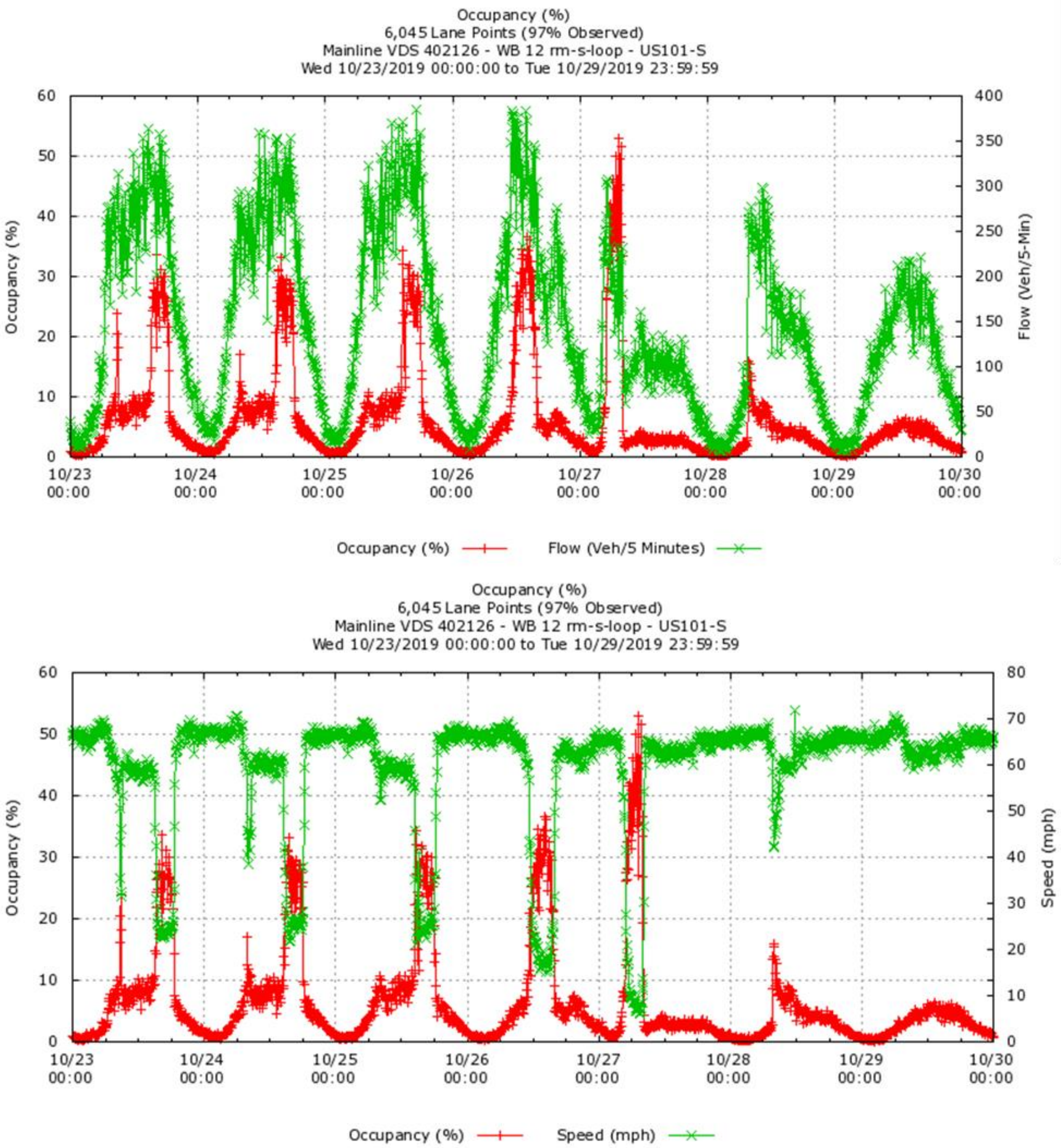


Figure 41 - Occupancy, flow and speed observed at WB12 rm-s-loop US101-S after fire ignition, taken from the PeMS database.

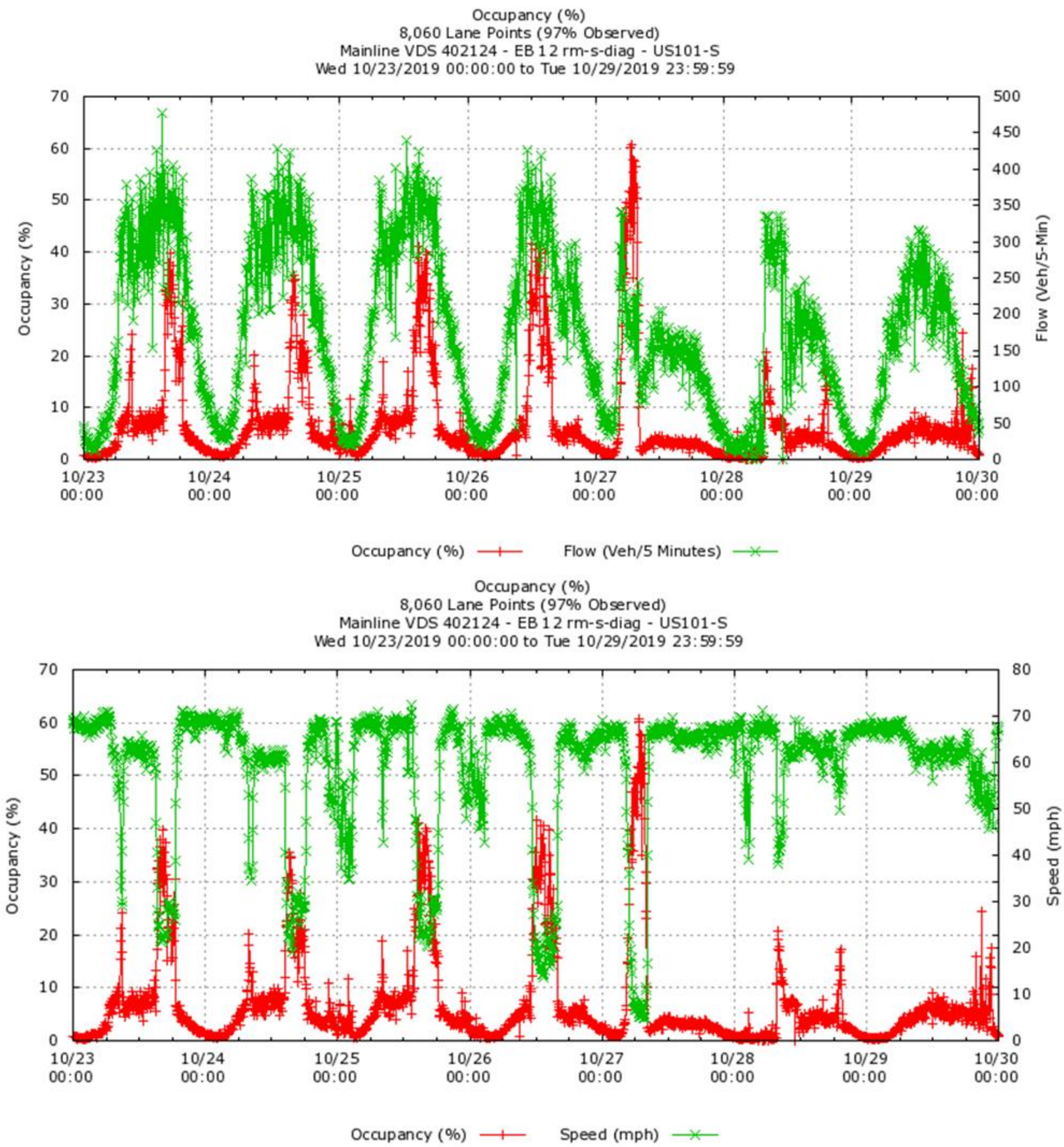
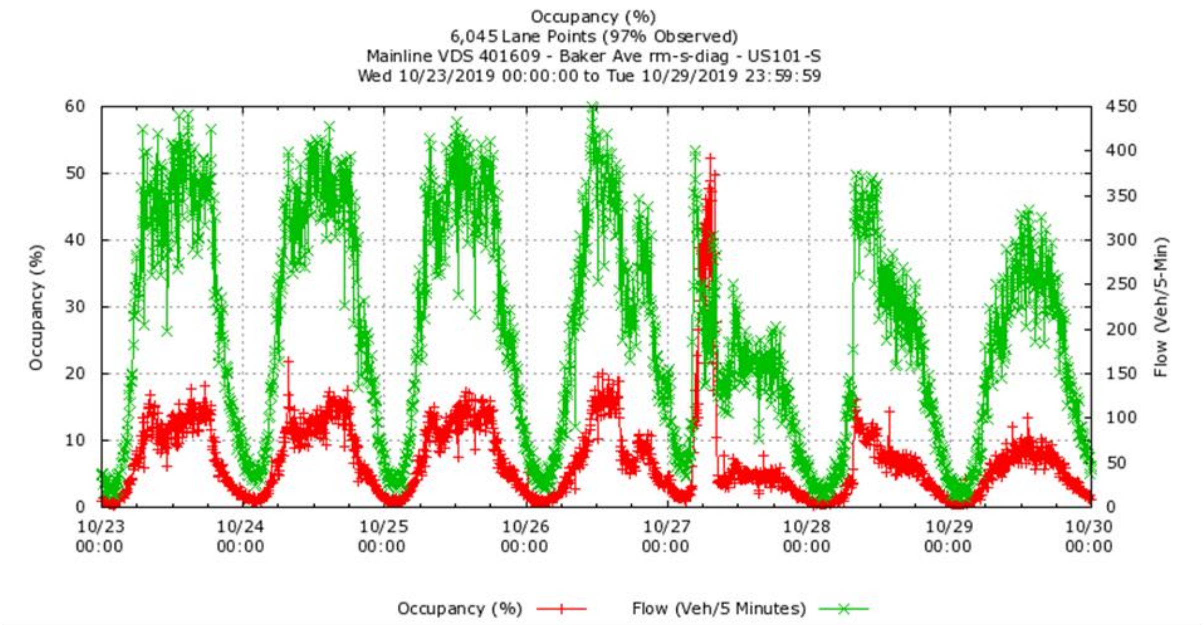


Figure 42 - Occupancy, flow and speed observed at EB12 rm-s-diag US101-S after fire ignition, taken from the PeMS database.



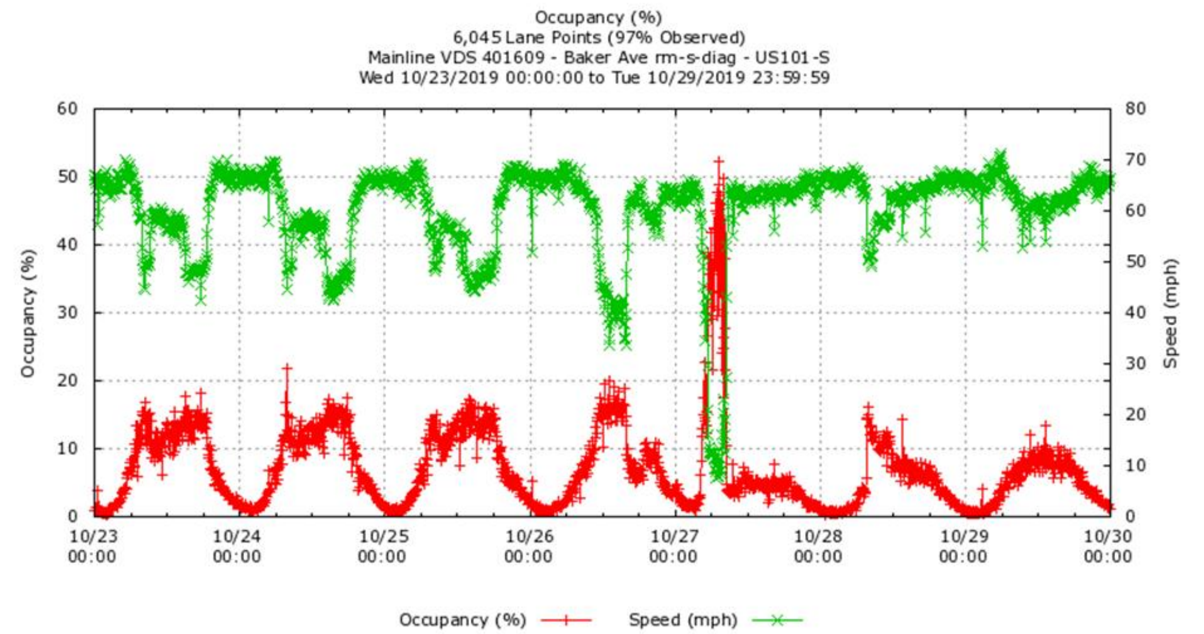
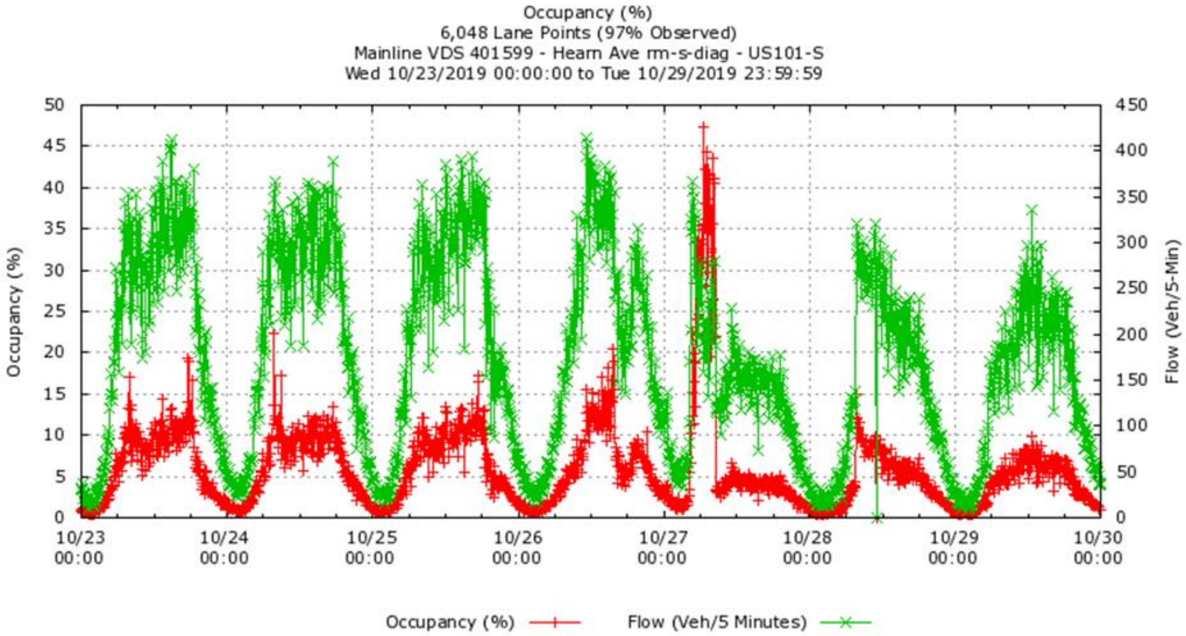


Figure 43 - Occupancy, flow and speed observed at Baker Ave rm-s-diag US101-S after fire ignition, taken from the PeMS database.



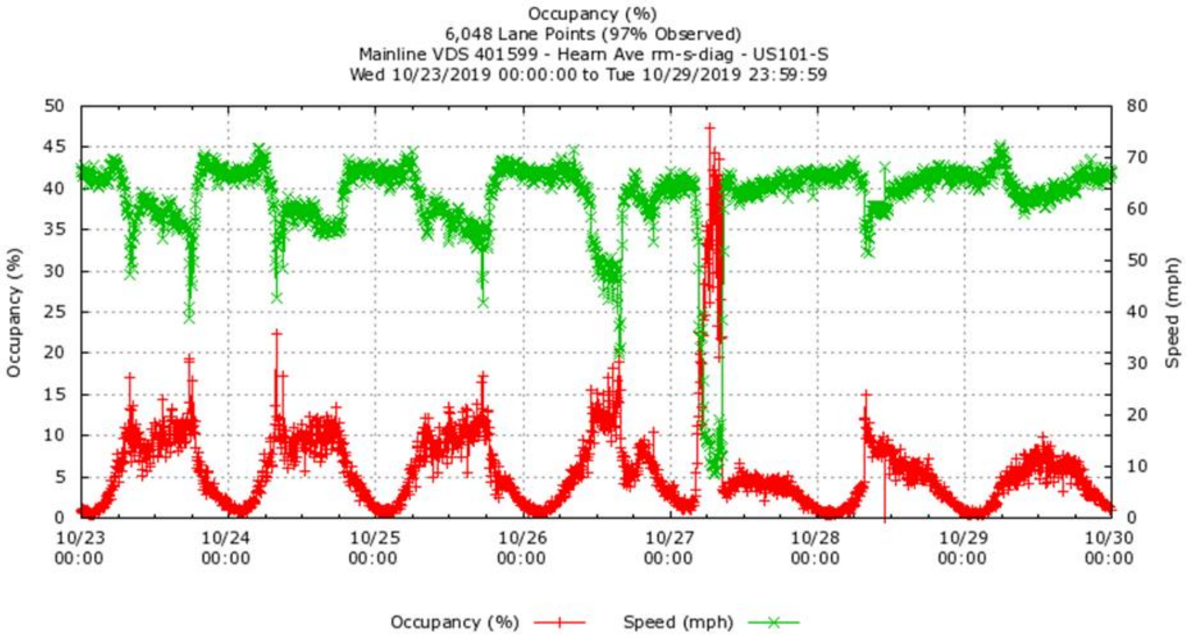


Figure 44 - Occupancy, flow and speed observed at Hearn Ave rm-s-diag US101-S after fire ignition, taken from the PeMS database.

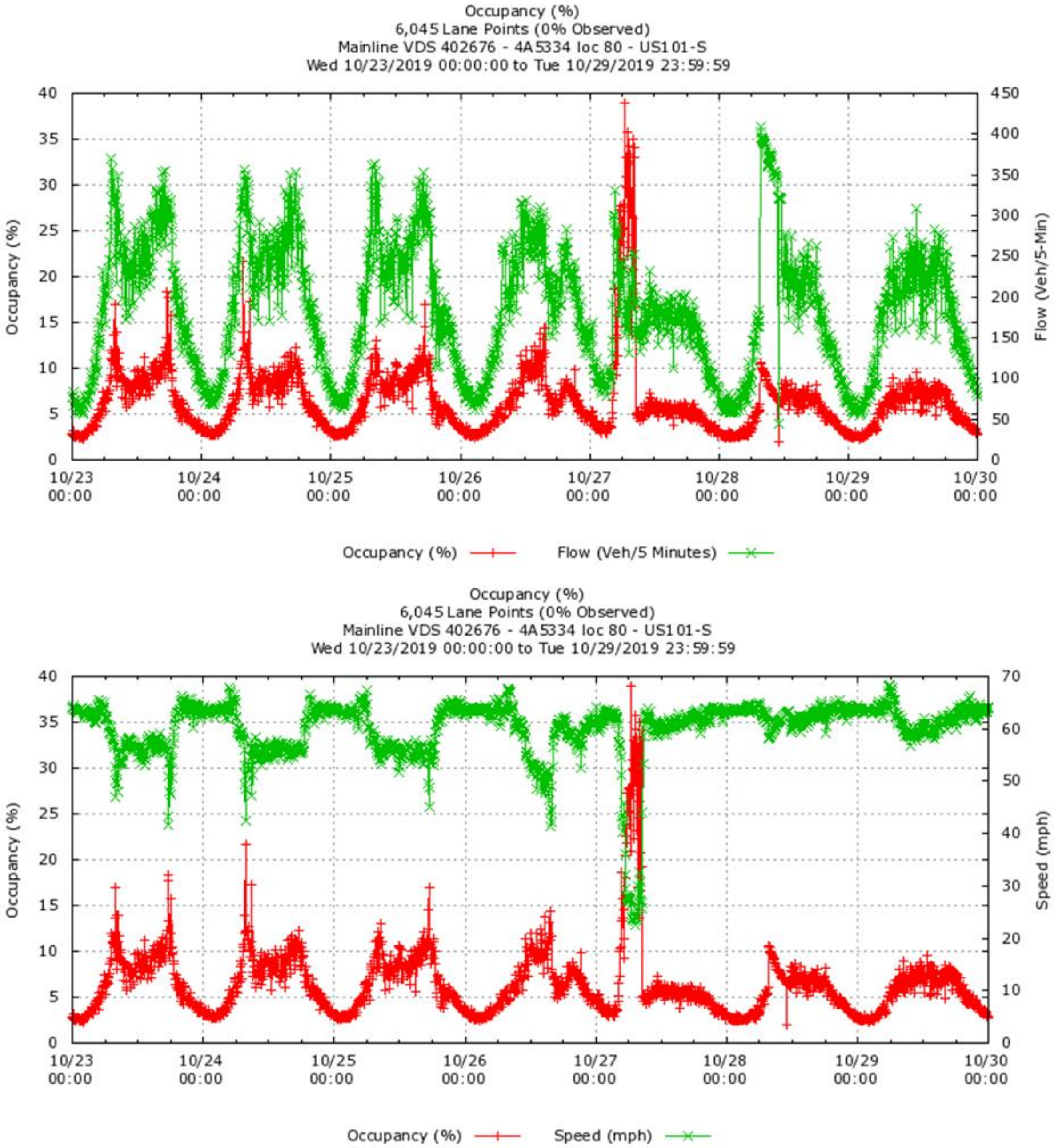
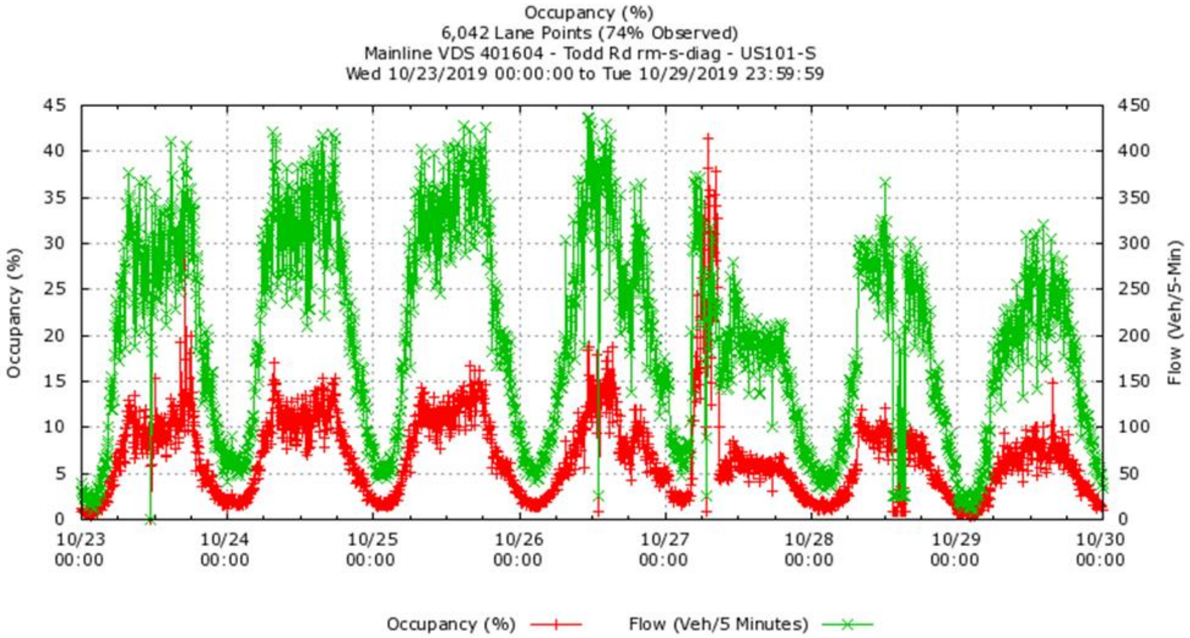


Figure 45 - Occupancy, flow and speed observed at 4A5334 loc 80 US101-S after fire ignition, taken from the PeMS database.



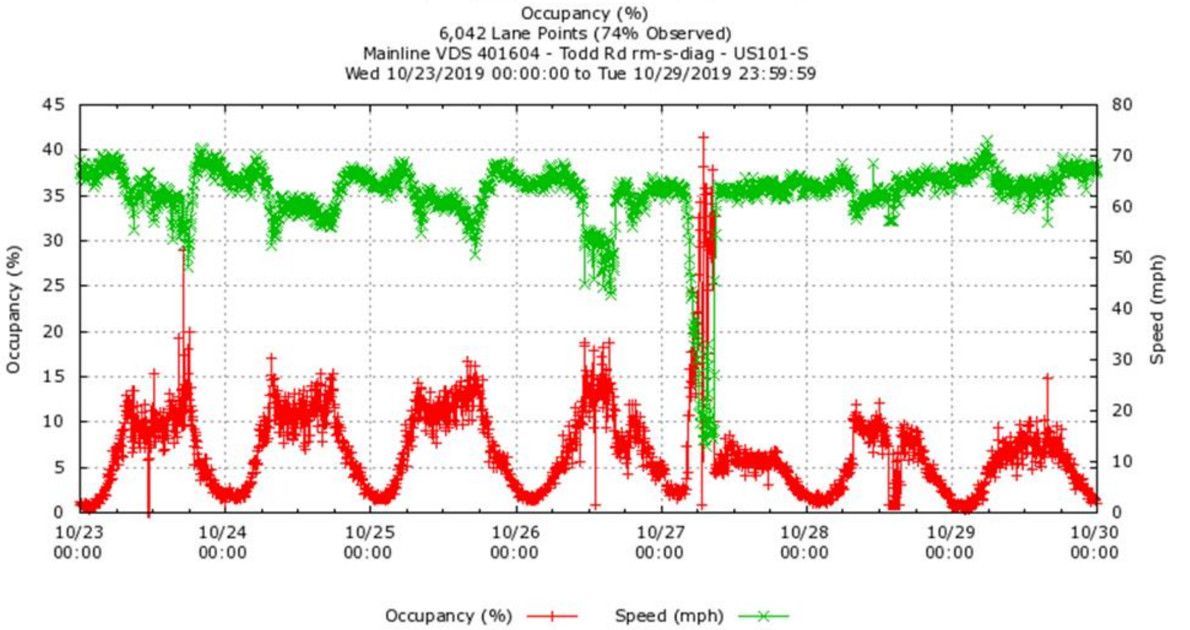


Figure 46 - Occupancy, flow and speed observed at Todd Rd rm-s-diag US101-S after fire ignition, taken from the PeMS database.

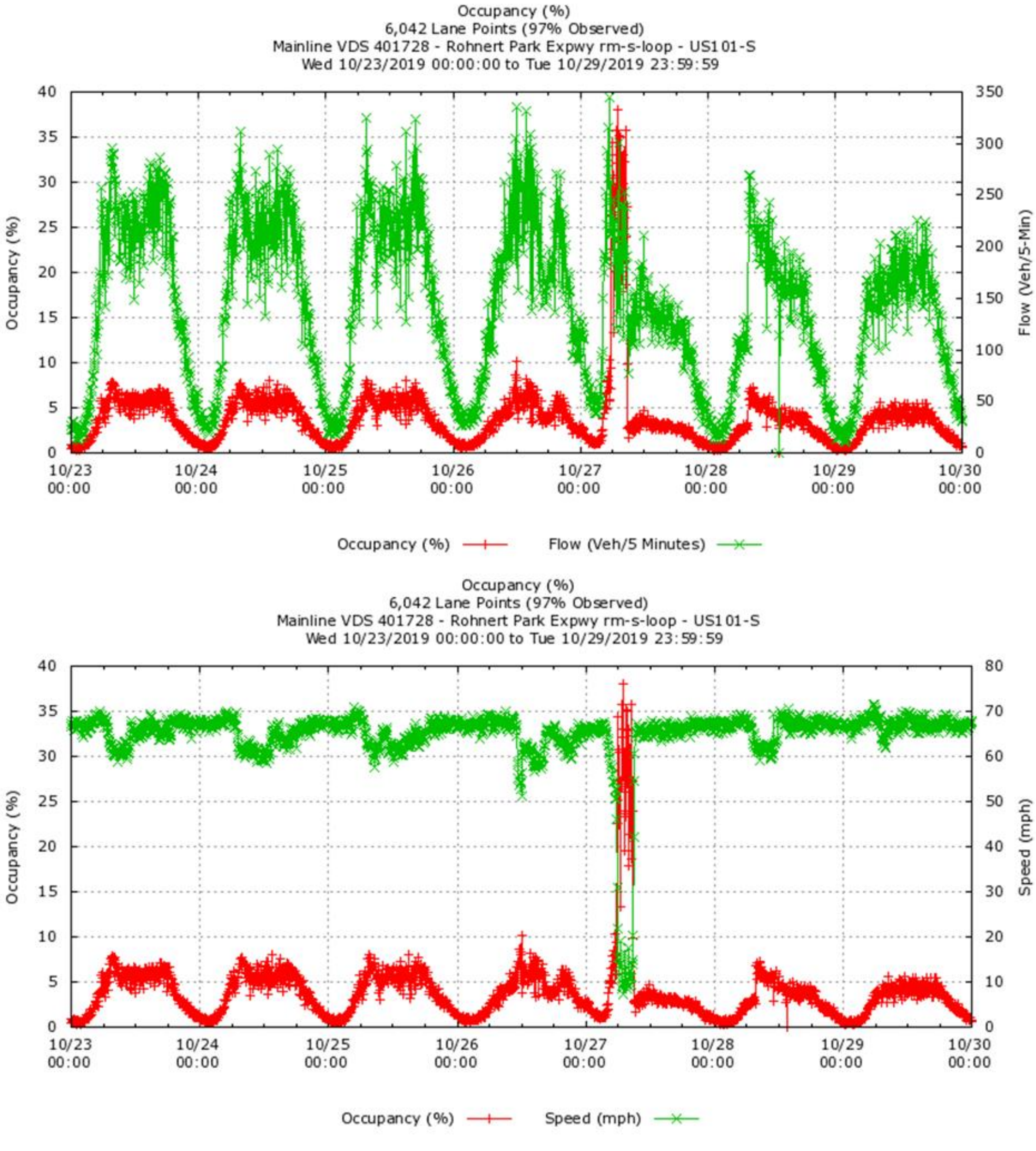


Figure 47 - Occupancy, flow and speed observed at Rohnert Park Expwy rm-s-loop US101-S after fire ignition, taken from the PeMS database.

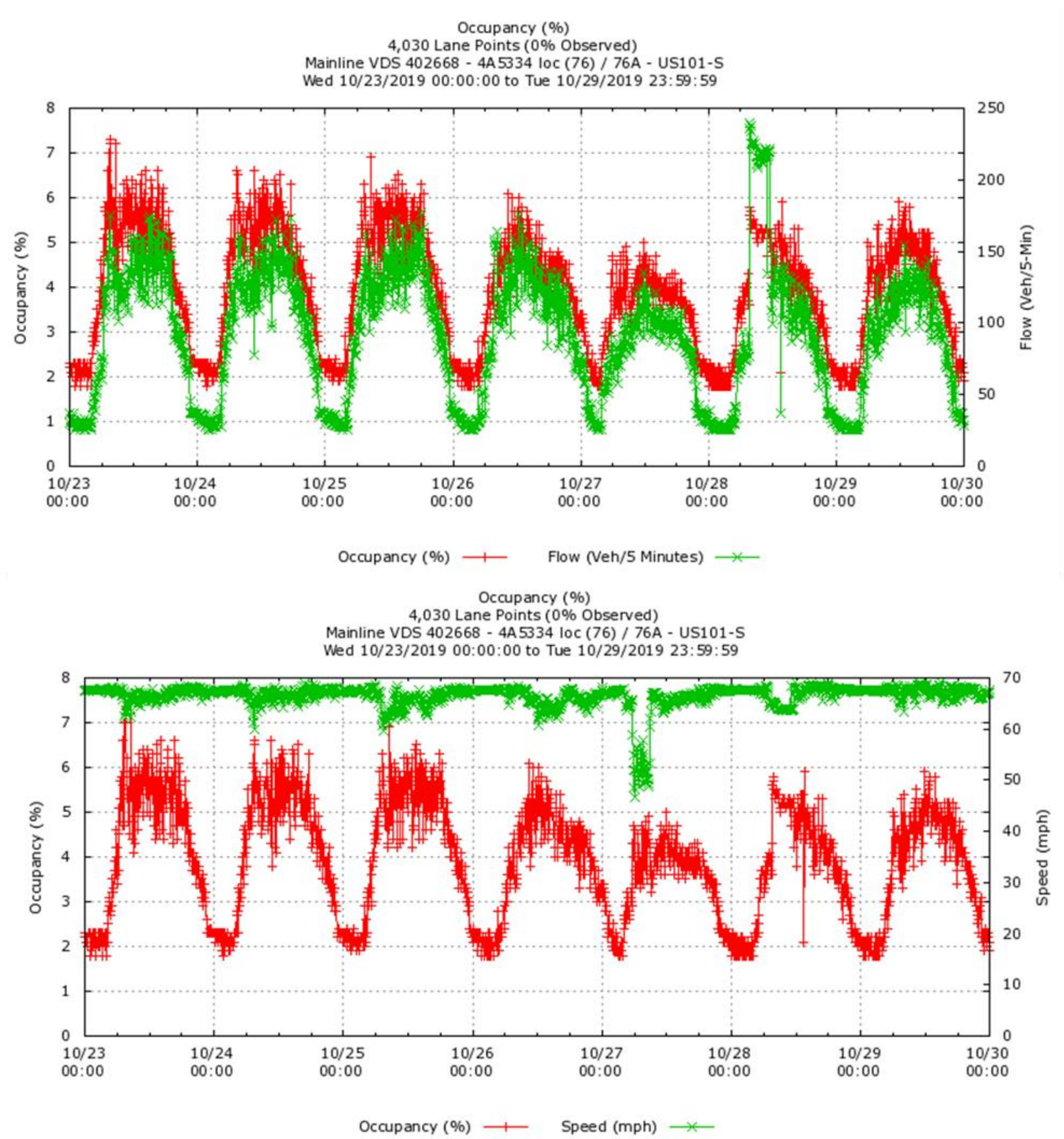


Figure 48 - Occupancy, flow and speed observed at 4A5334 loc (76)/76A US101-S after fire ignition, taken from the PeMS database.

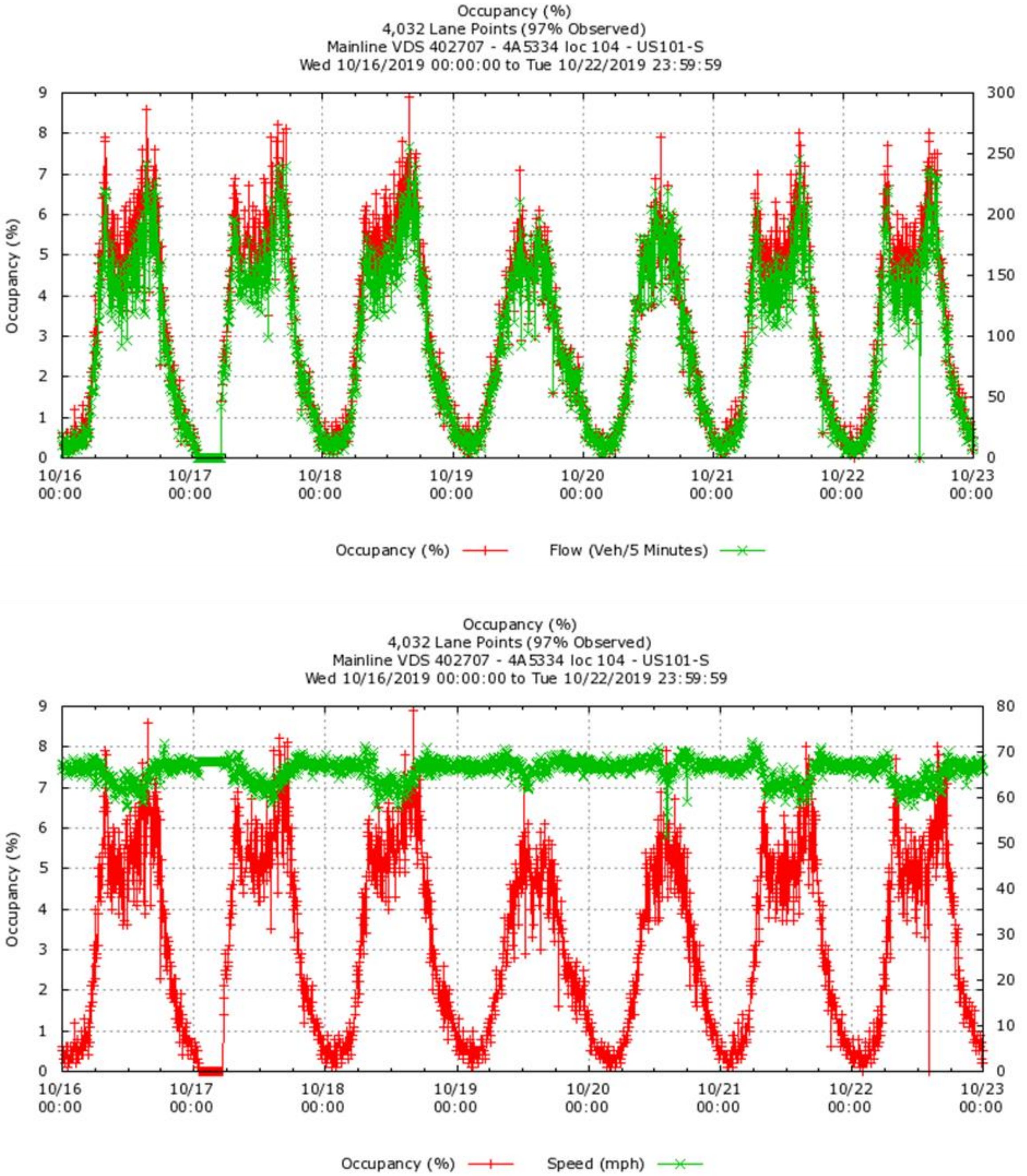


Figure 49 - Occupancy, flow and speed observed at 4A5334 loc 104 US101-S before fire ignition, taken from the PeMS database.

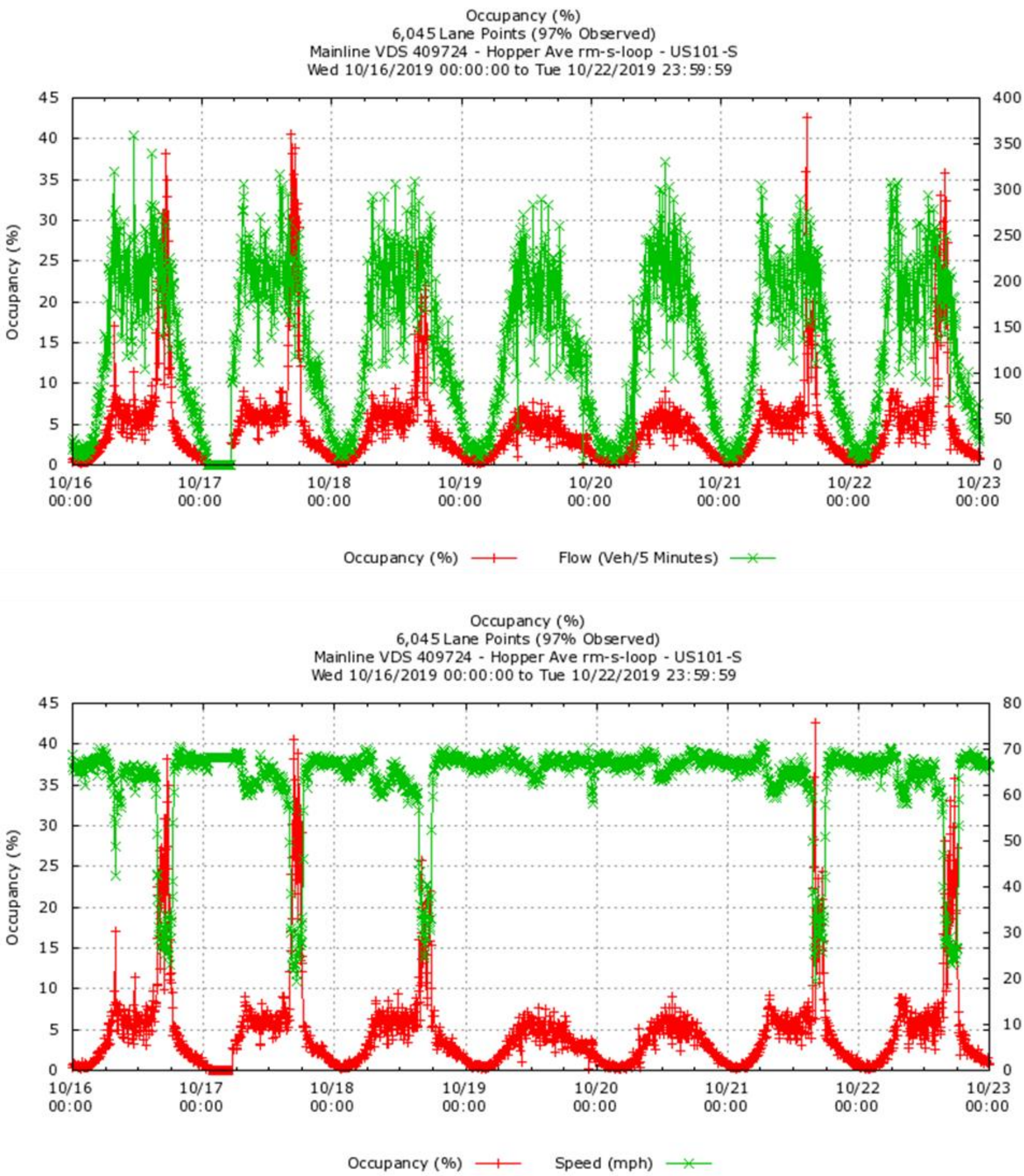


Figure 50 - Occupancy, flow and speed observed at Hopper Ave rm-s-loop US101-S before fire ignition, taken from the PeMS database.

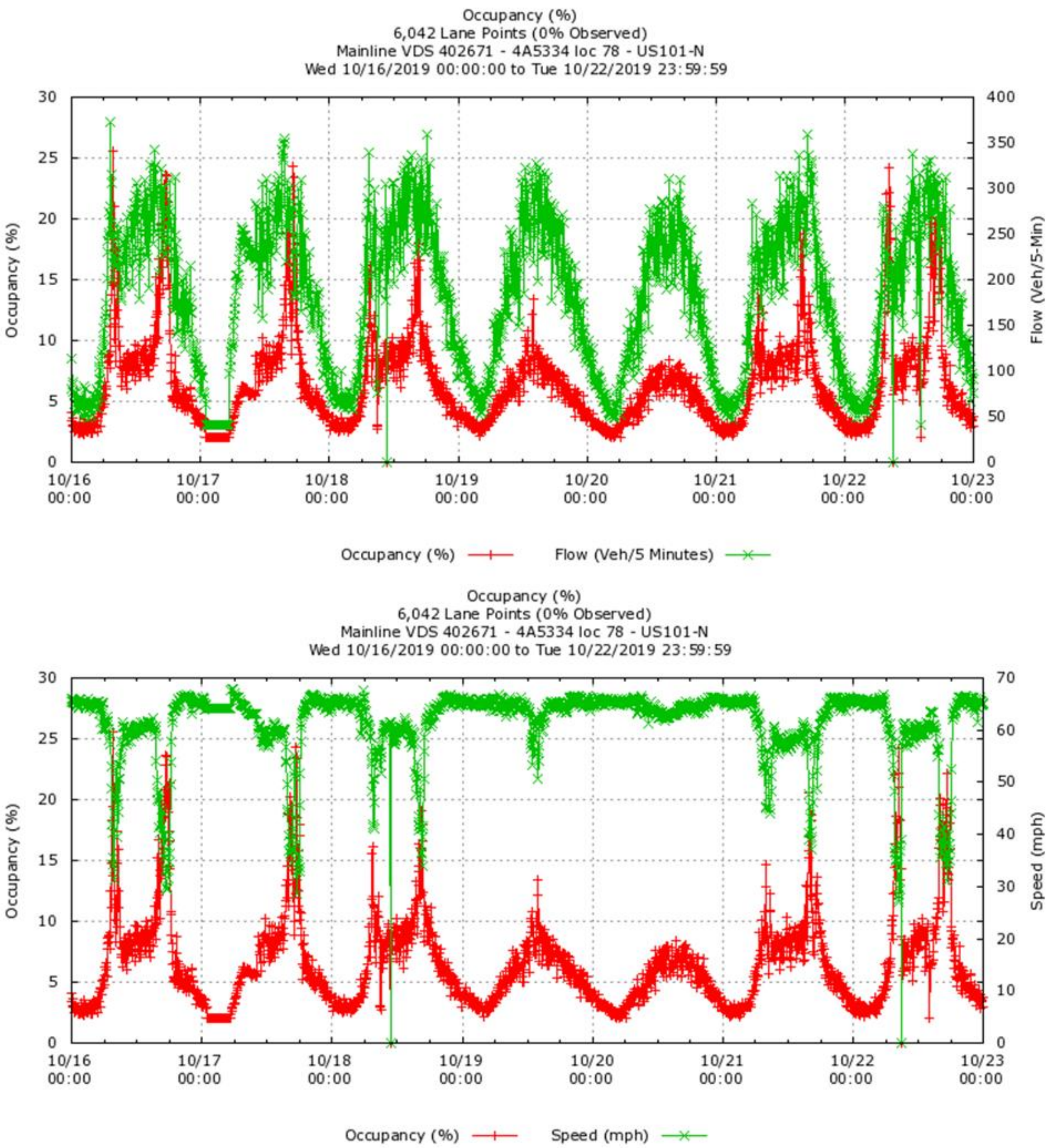
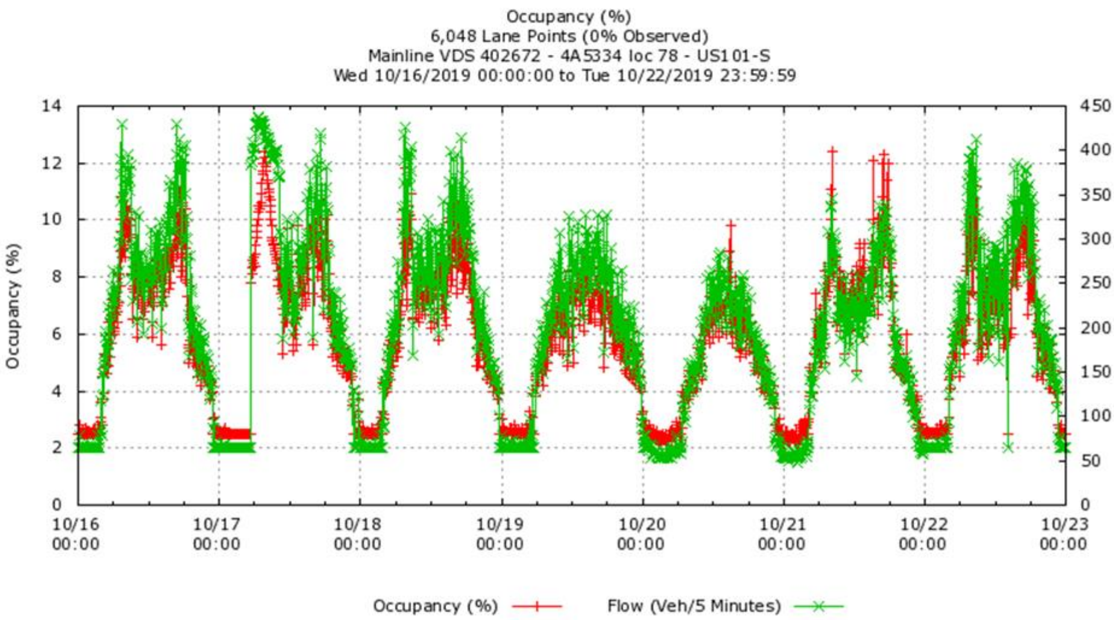


Figure 51 - Occupancy, flow and speed observed at 4A5334 loc 78 US101-N before fire ignition, taken from the PeMS database.



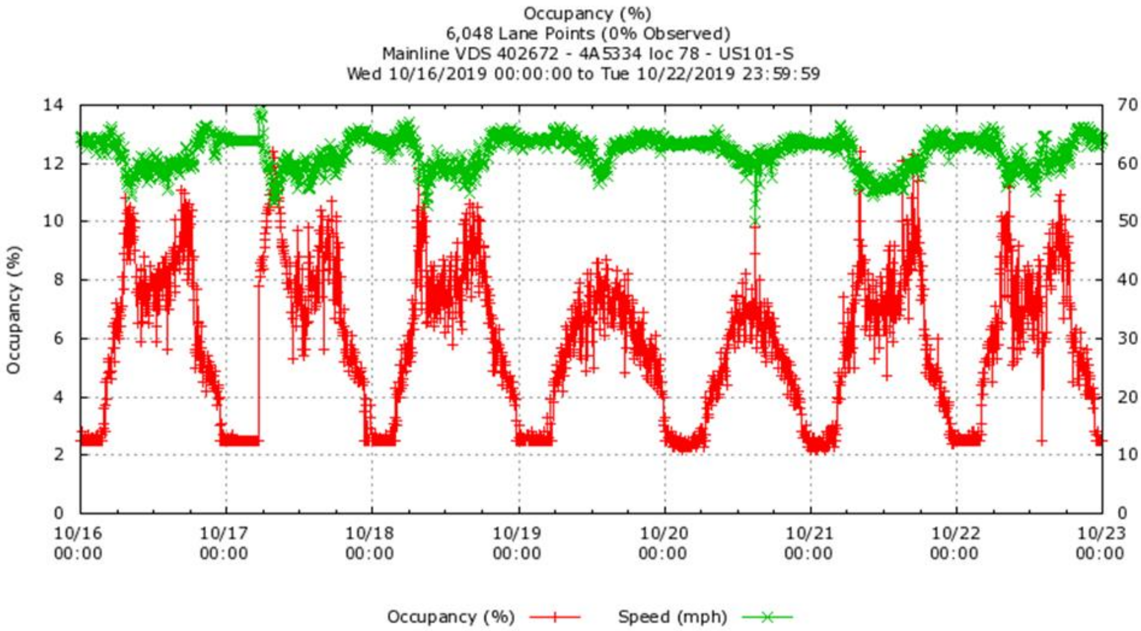
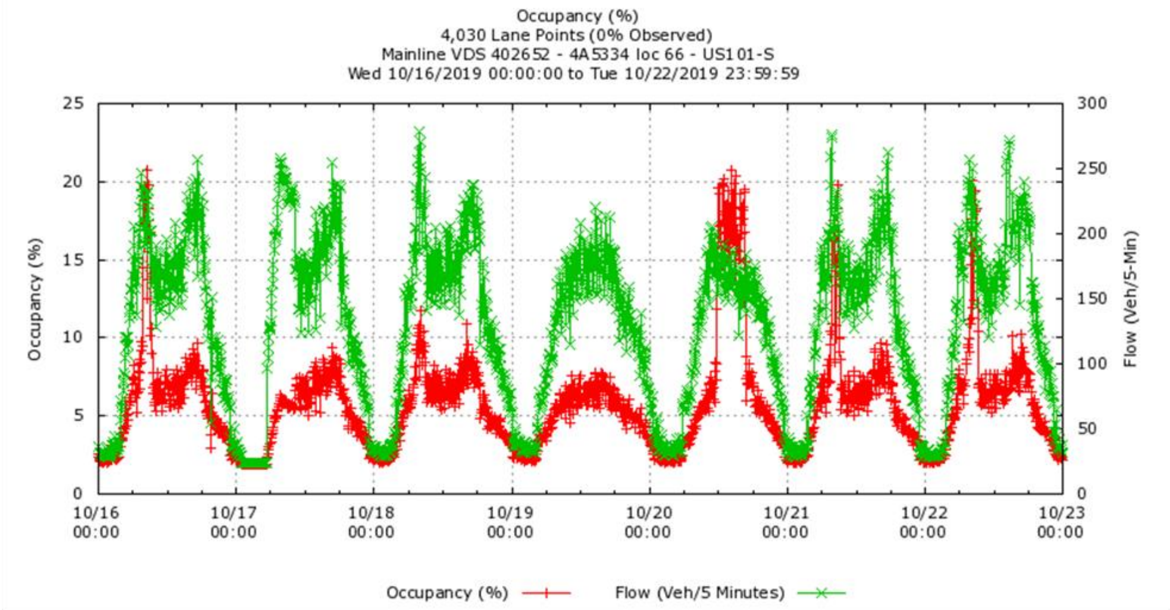


Figure 52 - Occupancy, flow and speed observed at 4A5334 loc 78 US101-S before fire ignition, taken from the PeMS database.



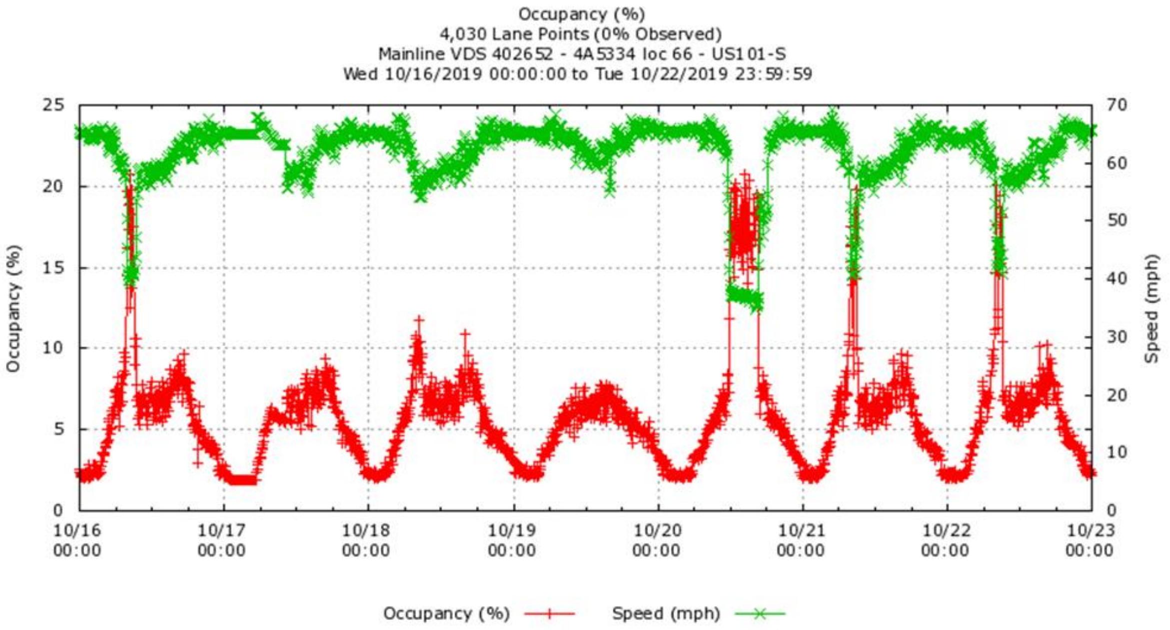
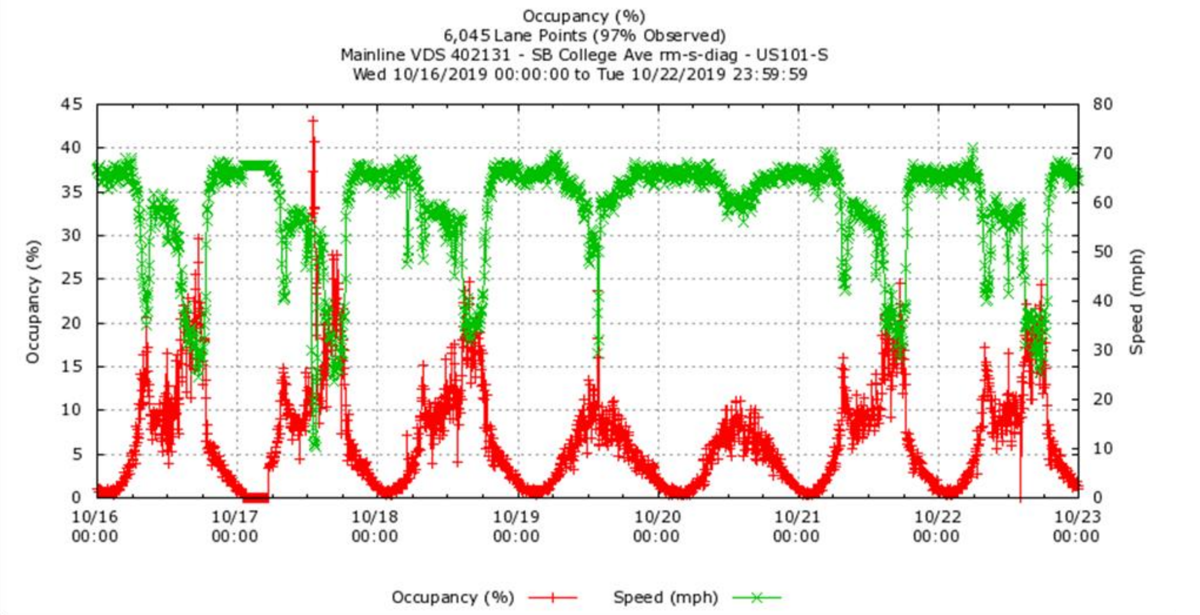


Figure 53 - Occupancy, flow and speed observed at 4A5334 loc 66 US101-S before fire ignition, taken from the PeMS database.



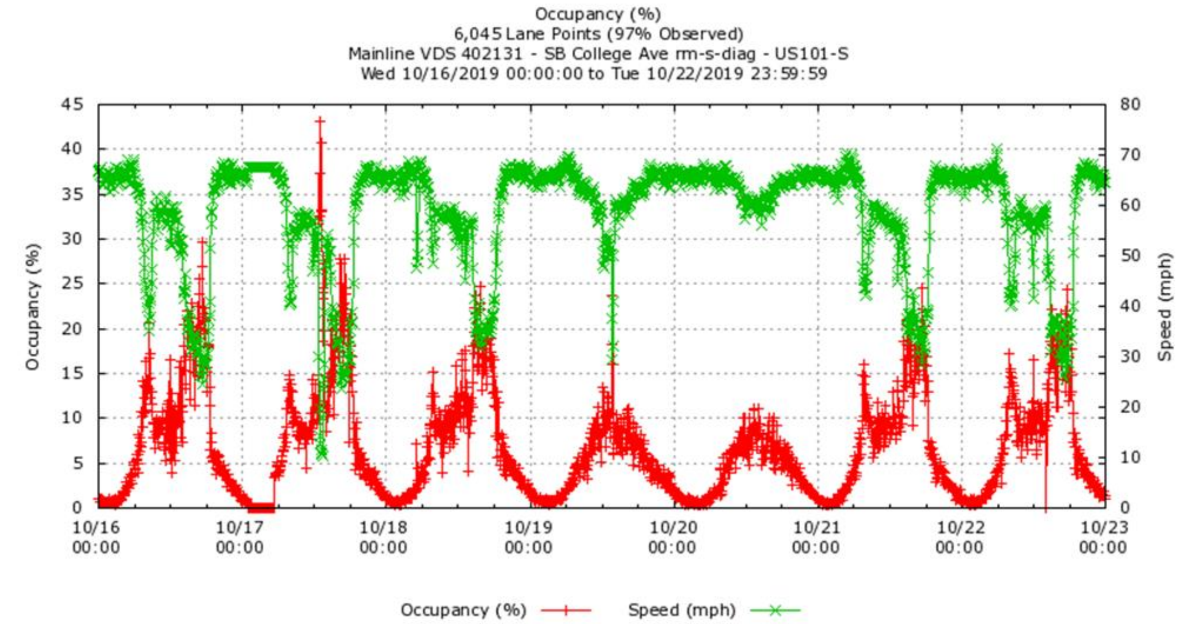


Figure 54 - Occupancy, flow and speed observed at SB College Ave rm-s-diag US101-S before fire ignition, taken from the PeMS database.

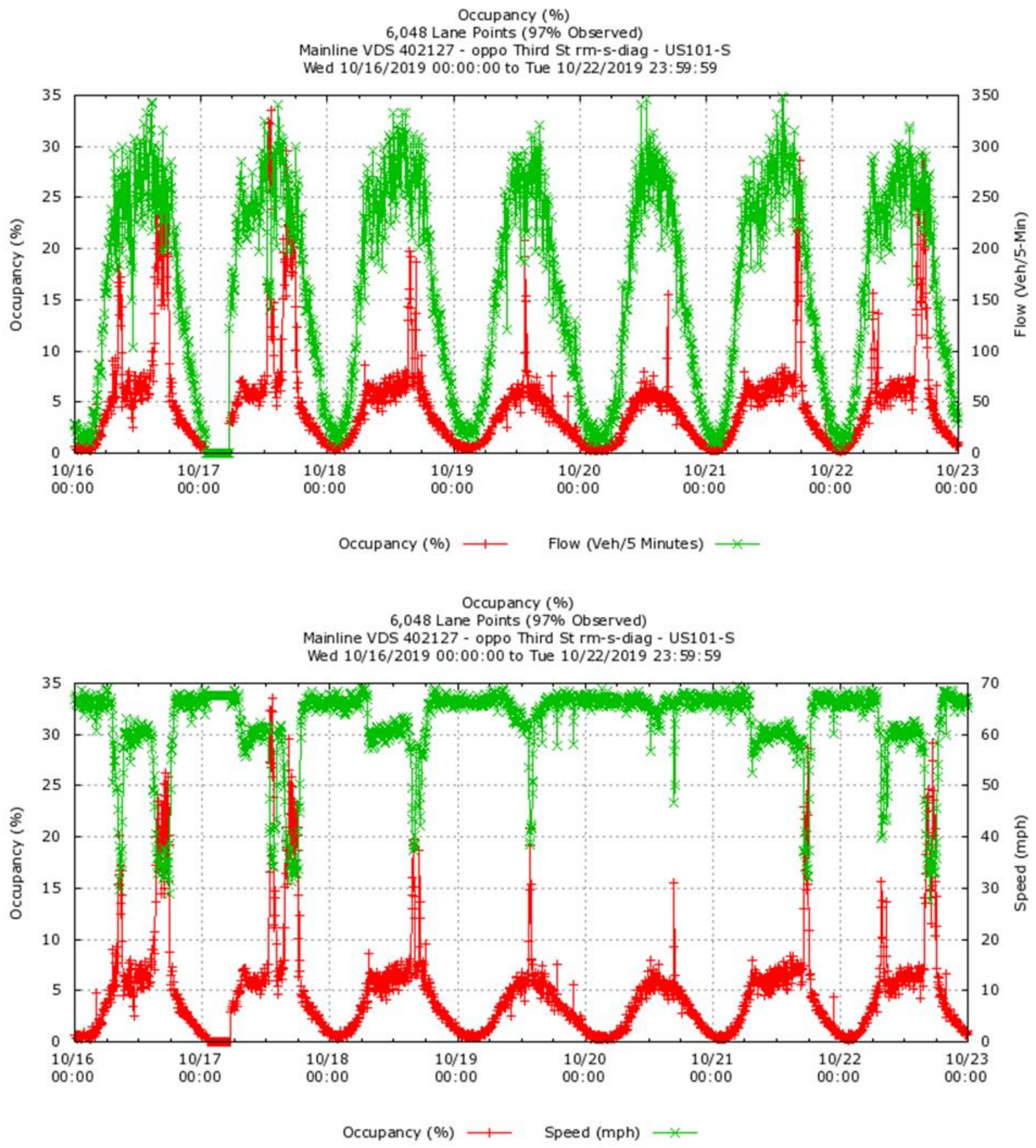


Figure 55 - Occupancy, flow and speed observed at Third St rm-s-diag US101-S before fire ignition, taken from the PeMS database.

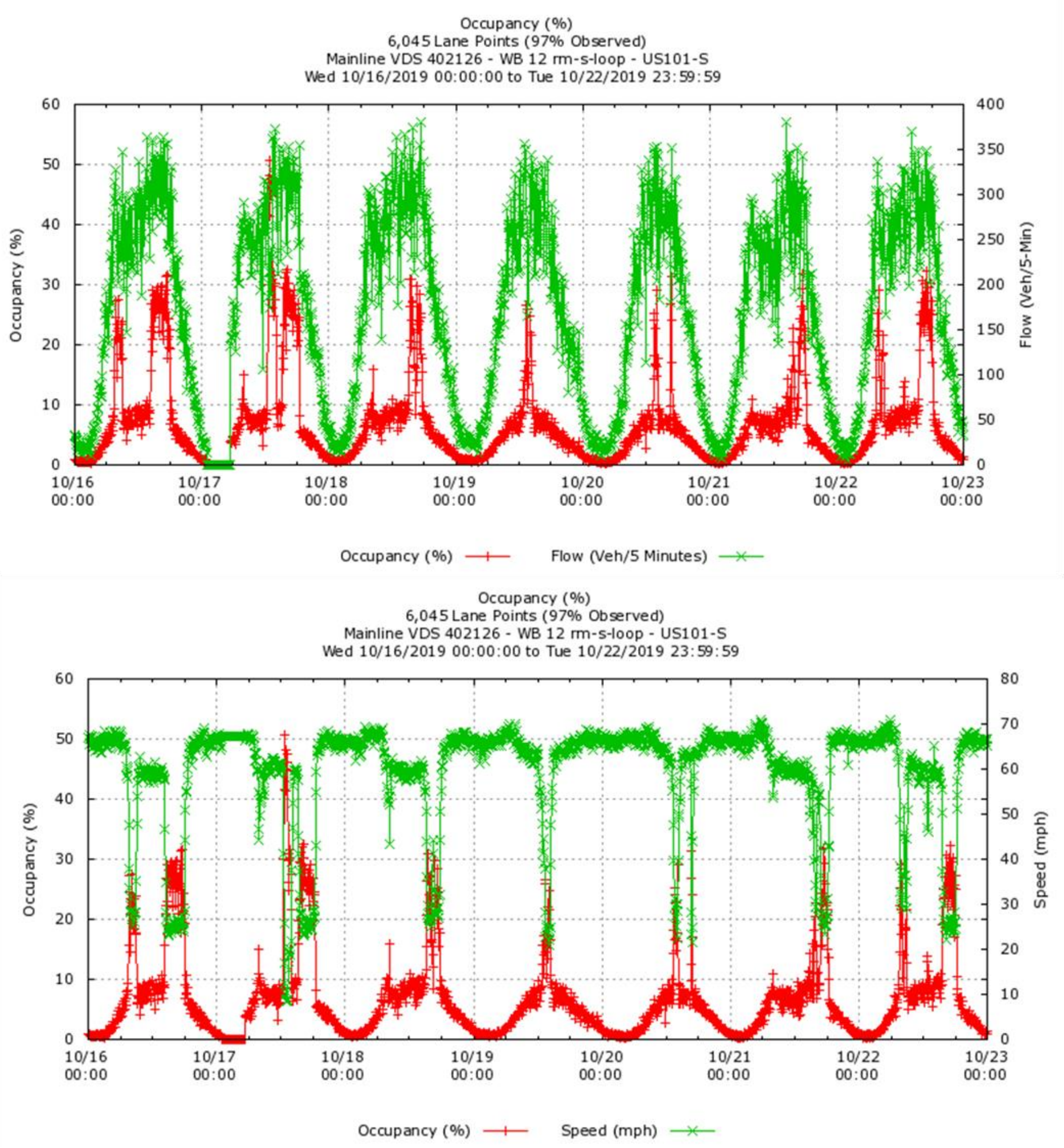


Figure 56 - Occupancy, flow and speed observed at WB 12 rm-s-loop US101-S before fire ignition, taken from the PeMS database.

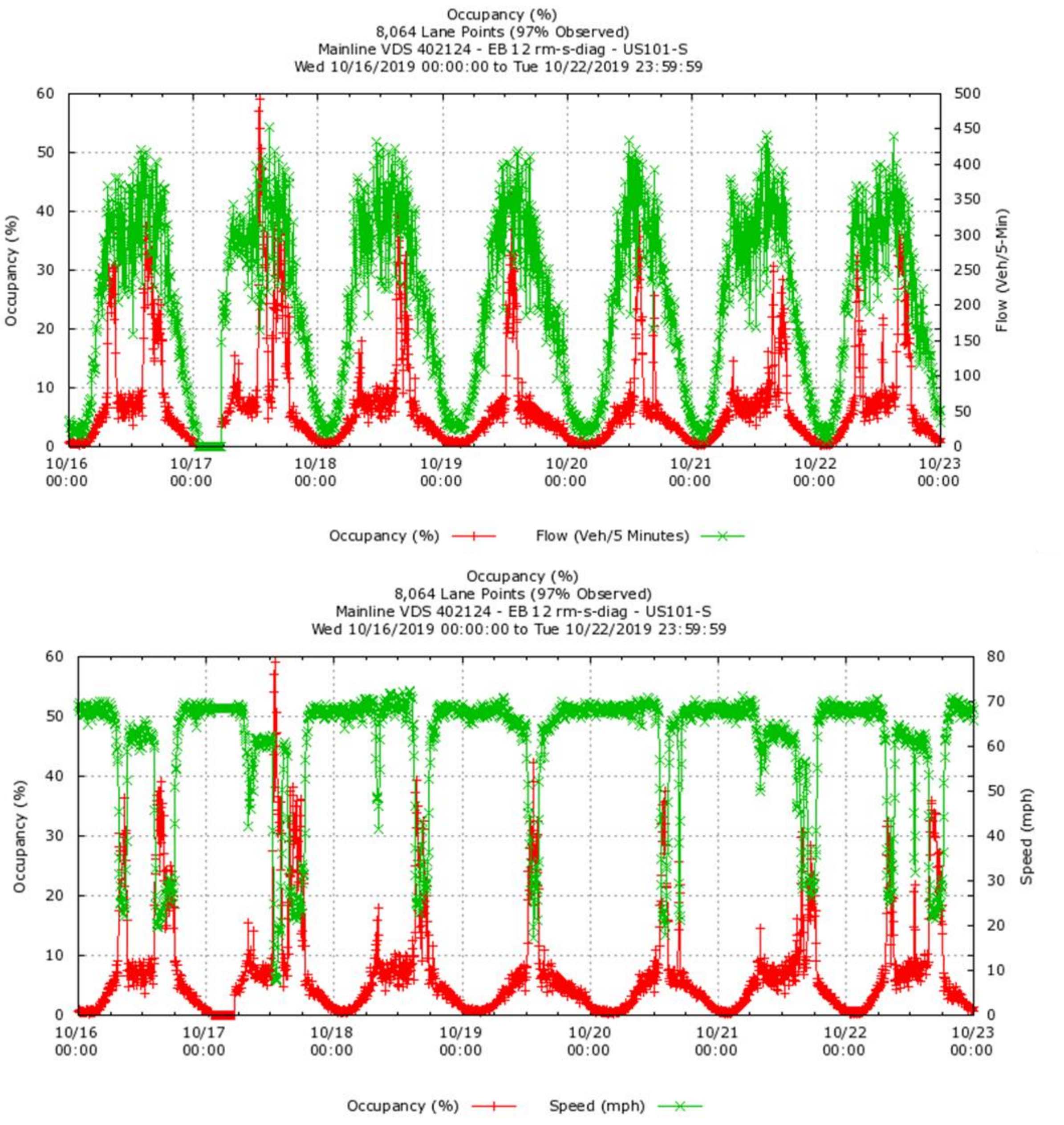


Figure 57 - Occupancy, flow and speed observed at EB 12 rm-s-diag US101-S before fire ignition, taken from the PeMS database.

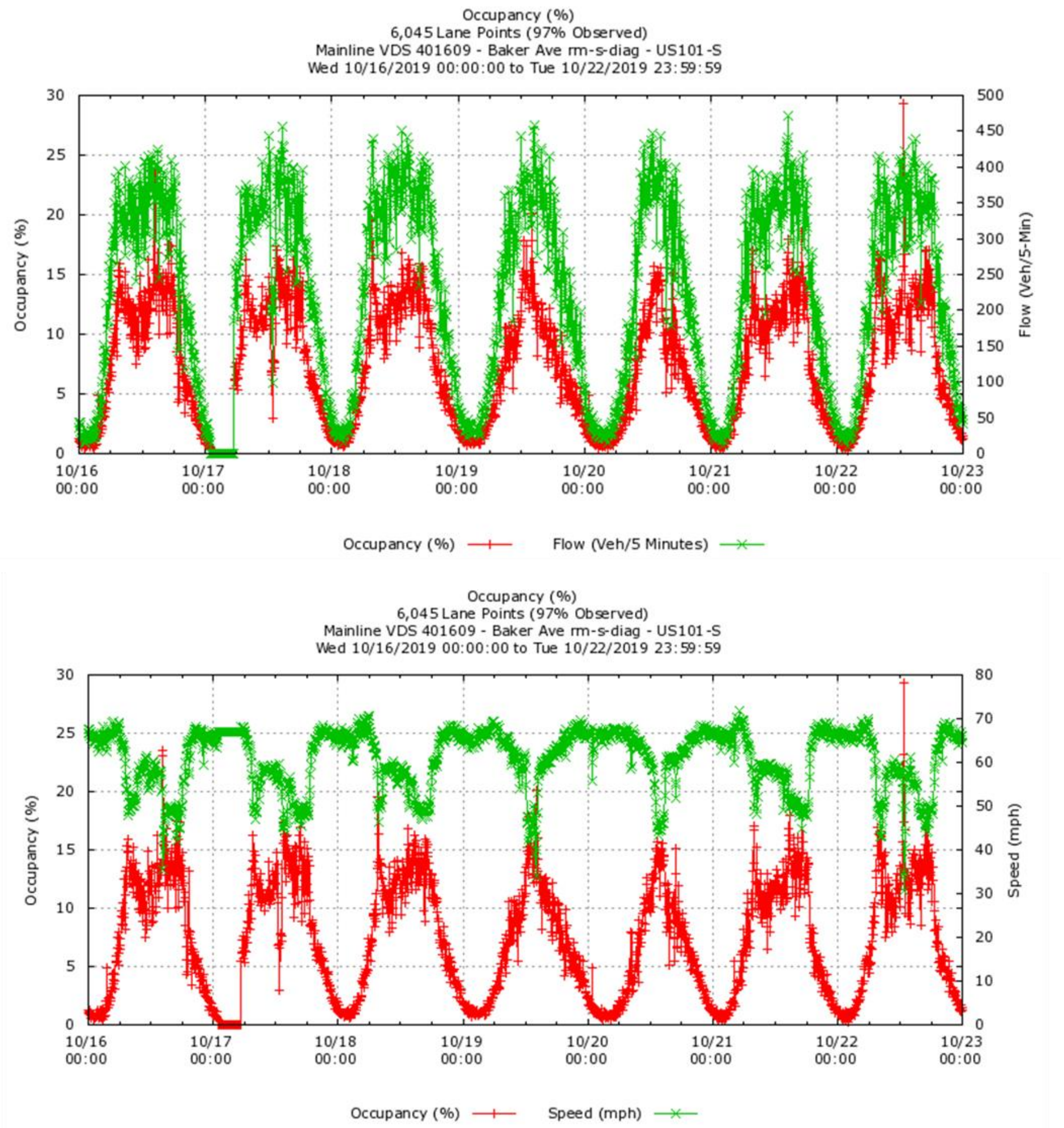
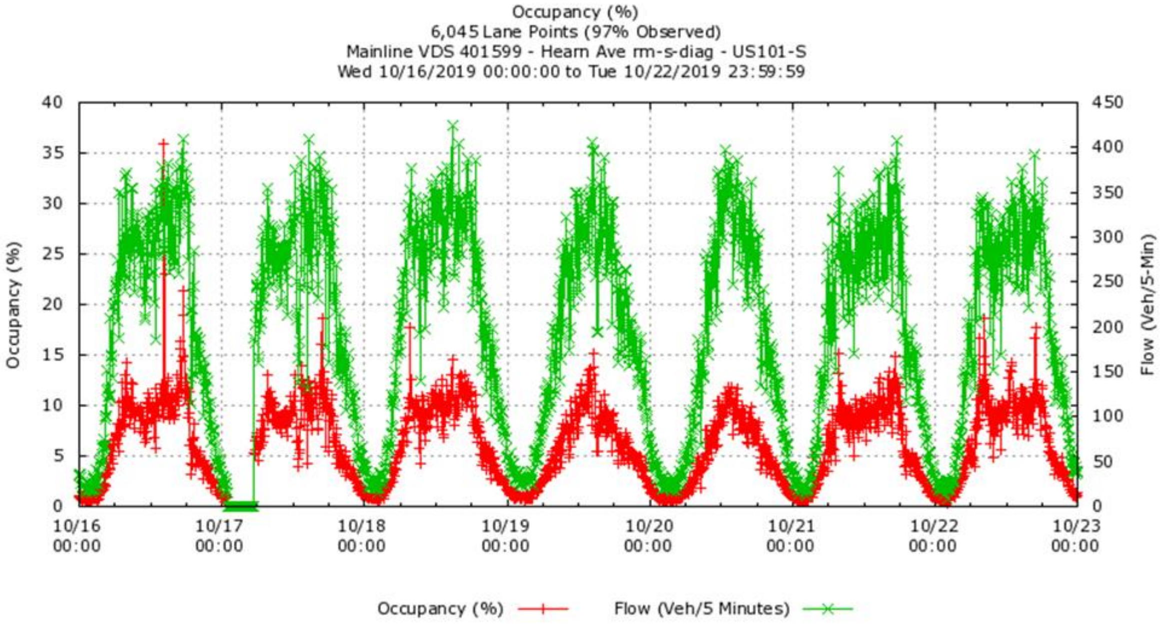


Figure 58 - Occupancy, flow and speed observed at Baker Ave rm-s-diag US101-S before fire ignition, taken from the PeMS database.



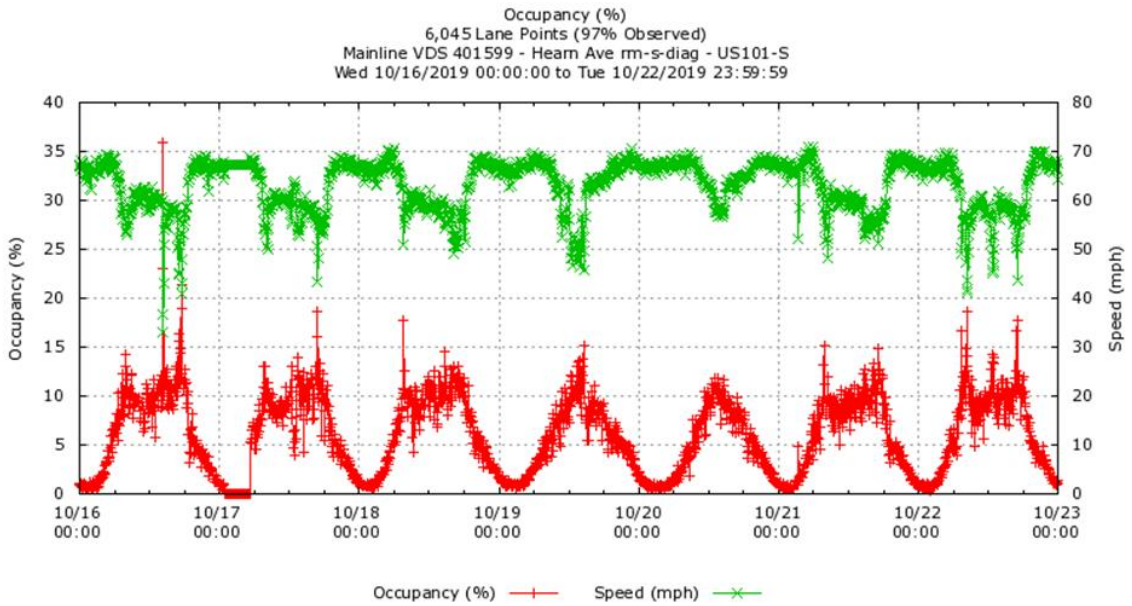
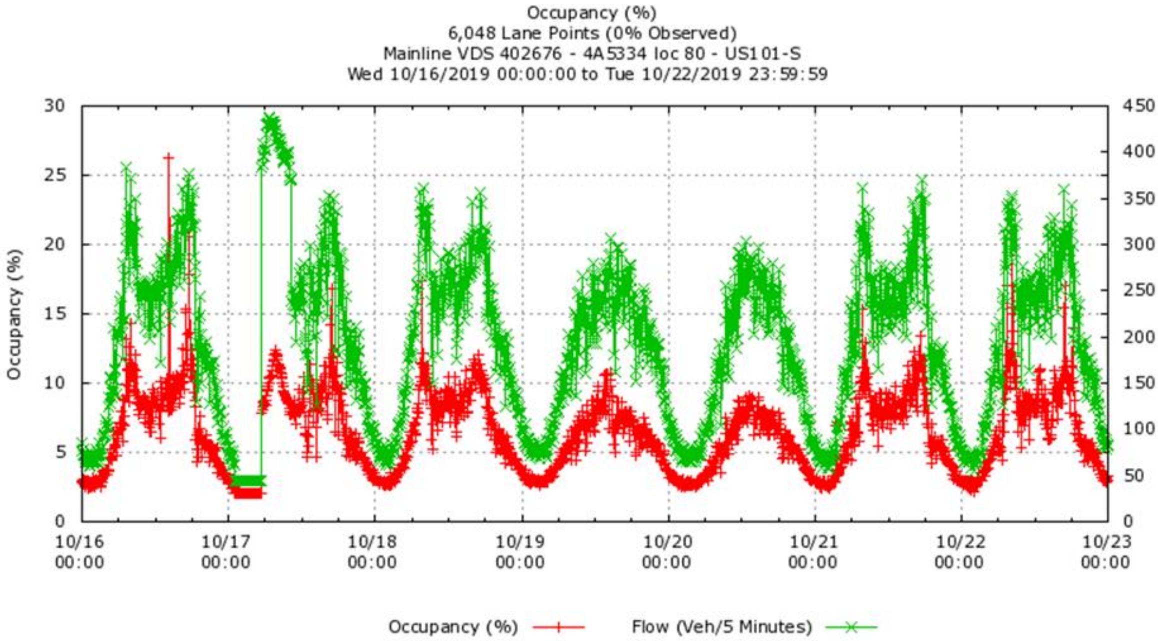


Figure 59 - Occupancy, flow and speed observed at Hearn Ave rm-s-diag US101-S before fire ignition, taken from the PeMS database.



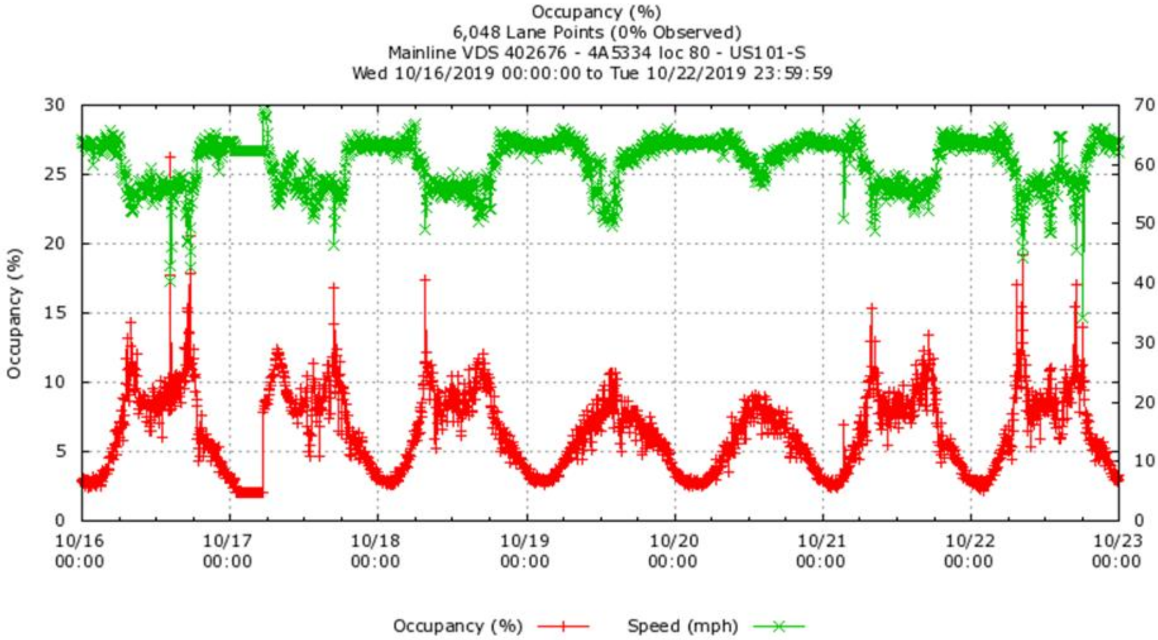
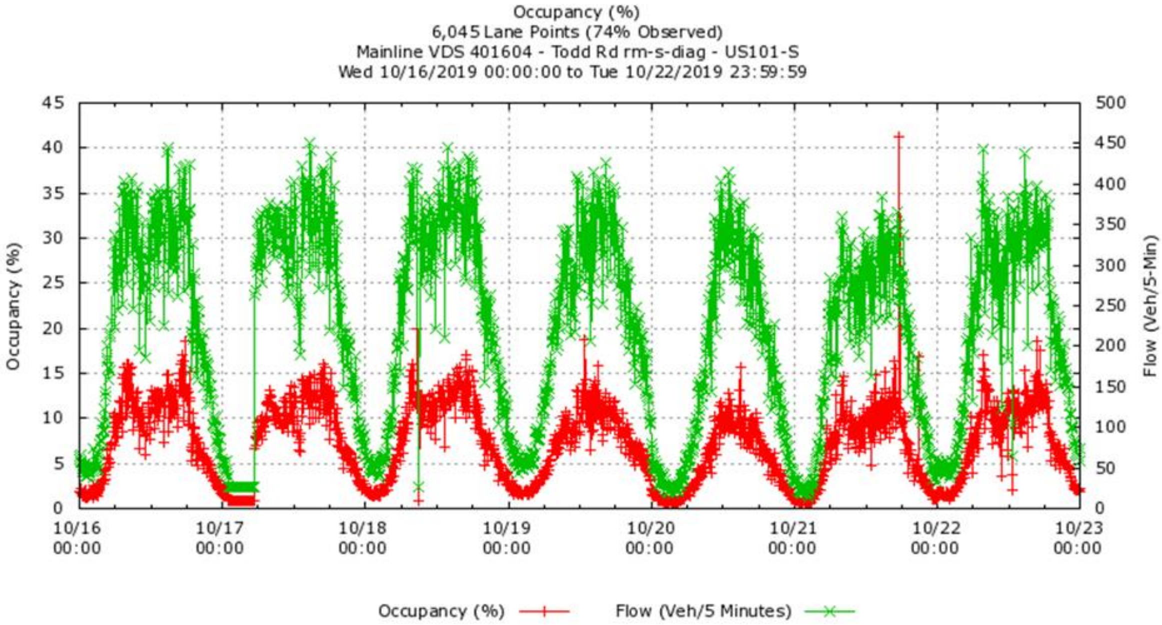


Figure 60 - Occupancy, flow and speed observed at 4A5334 loc 80 US101-S before fire ignition, taken from the PeMS database.



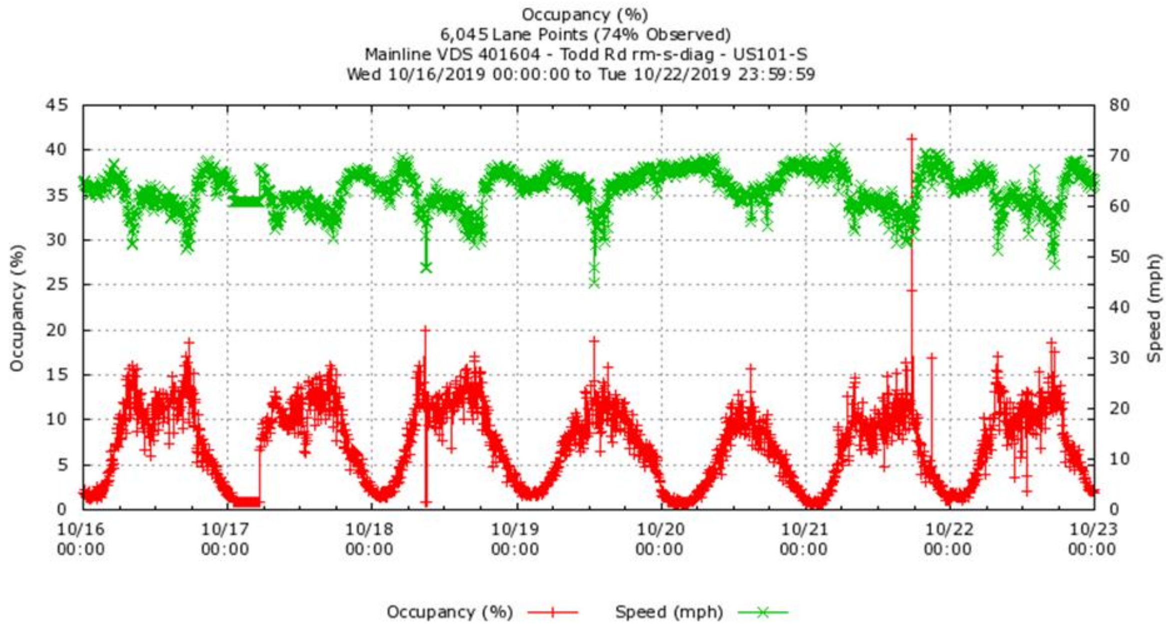


Figure 61 - Occupancy, flow and speed observed at Todd Rd rm-s-diag US101-S before fire ignition, taken from the PeMS database.

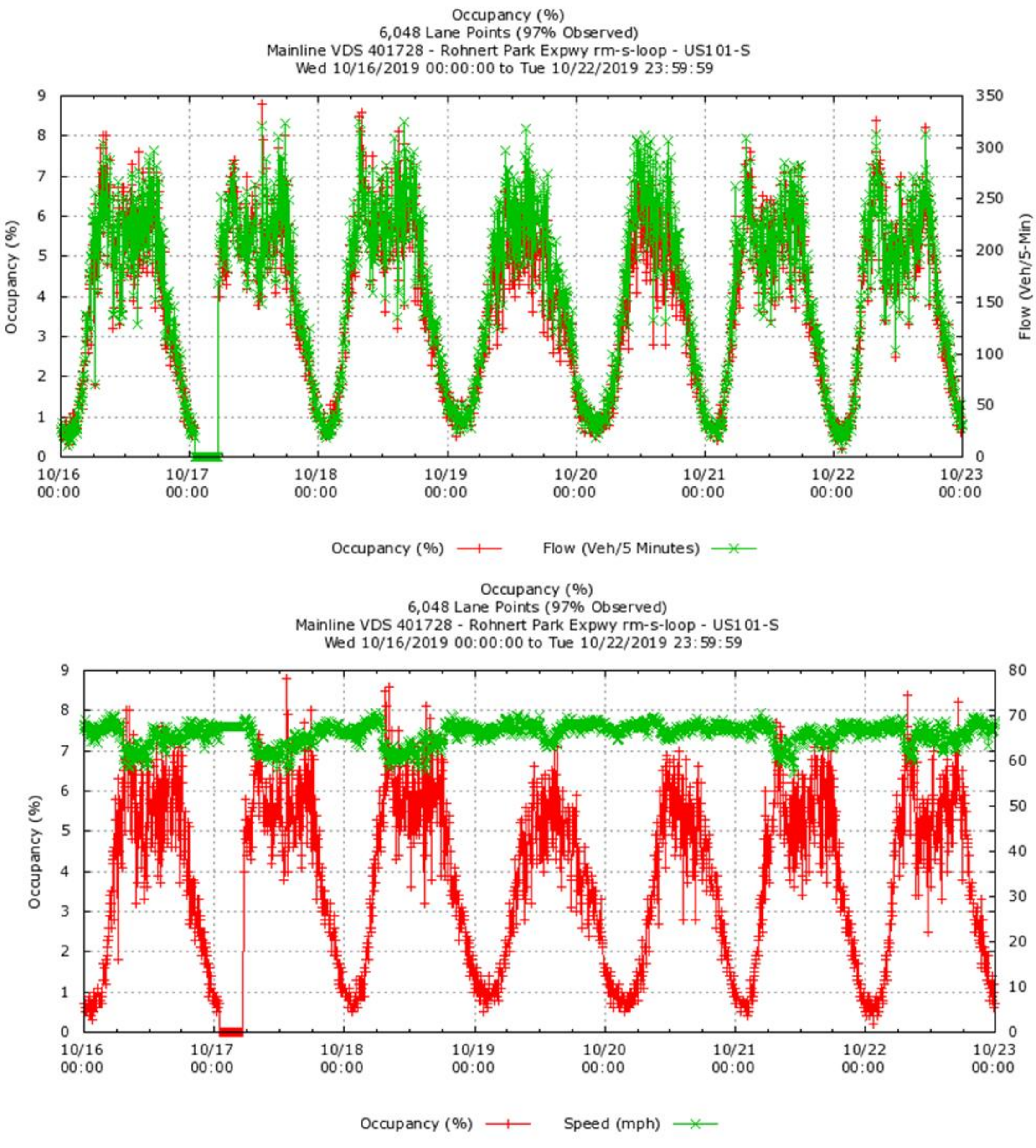
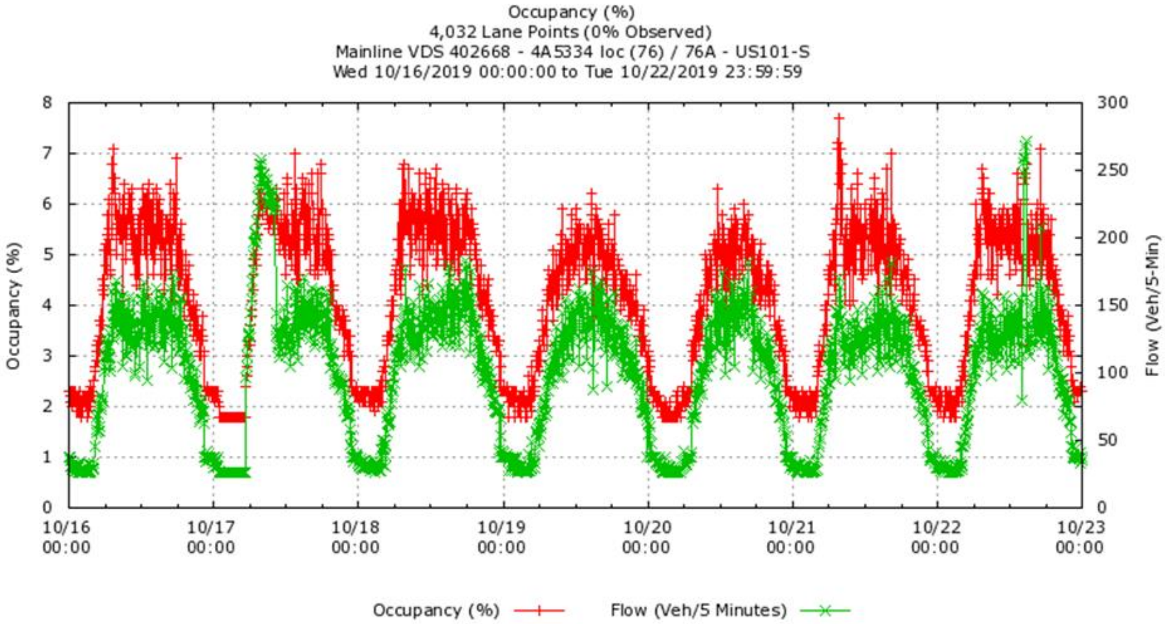


Figure 62 - Occupancy, flow and speed observed at Rohnert Park Expwy rm-s-loop US101-S before fire ignition, taken from the PeMS database.



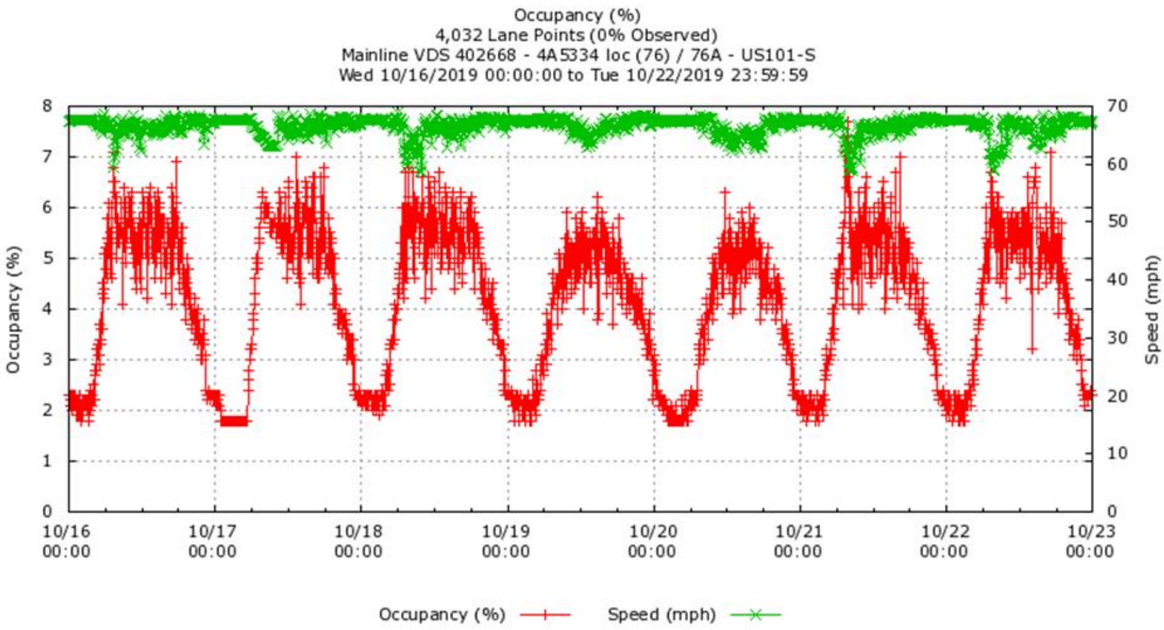


Figure 63 - Occupancy, flow and speed observed at 4A5334 loc (76)/76A US101-S before fire ignition, taken from the PeMS database.